❖ Basic Concepts

Energy conversion means converting one form of energy into another form. An electric generator converts mechanical energy (drawn from prime mover through shaft) into electric energy. An electric motor converts electric energy into mechanical energy (which drives mechanical load e.g. Fan, lathe etc.).

Electric generators and motors operate by virtue of induced emf. The induction of emf is based on Faraday's law of electromagnetic induction. Every generator and motor has a stator (which remains stationary) and rotor (which rotates).

❖ Faraday's Law of Electromagnetic Induction

Michael Faraday demonstrated through his experiments that an emf is induced in a circuit when the magnetic flux enclosed by the circuit changes with respect to time. In 1831, he proposed the following law known as Faraday's law of electromagnetic induction.

$$e= \frac{d\lambda}{dt}= \frac{Nd\phi}{dt} \tag{1.1}$$

e = induced voltage in volts

λ = flux linkage, weber turns

N = number of turns in the winding

ϕ = flux, webers

t = time, seconds

❖ Lenz's Law

Every action causes an equal and opposite reaction. The fact that this is true in electromagnetism was discovered by Emil Lenz. The Lenz's law states that the induced current always develops a flux which opposes the motion (or the change producing the induced current). This law refers to induced currents and thus implies that it is applicable to closed circuits only. If the circuit is open, we can find the direction of induced emf by thinking in terms of the response if it were closed.

The motion of a conductor in a field causes an induced emf in the conductor and energy is generated. This is possible if work is done in moving the conductor through the field. If work is to be done, a force must oppose the motion of conductor. This opposing force is due to flux set up by induced current. Figure 1.1a illustrates Lenz's law. The motion of conductor causes the deflection of galvanometer to the left. This indicates that direction of

induced emf and current are as shown. The current causes a flux in the clockwise direction as shown. This flux strengthens the magnetic field above the conductor and weakens that below it. Thus a force in the downward direction acts on the conductor (Fig. 1.1b). The motion of the conductor is opposed by the magnetic flux due to induced current. Since induced emf opposes the change in flux, a negative sign is sometimes added in Eq. (1.1). If it is kept in view that direction of induced emf is such as to oppose the change in flux, there is no need of negative sign.

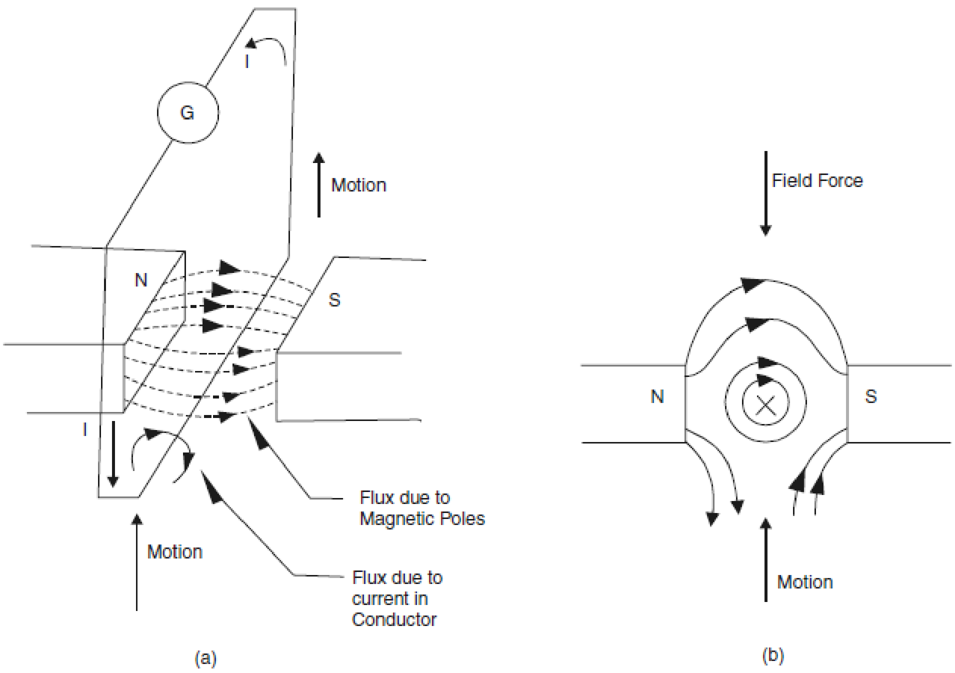


Fig. 1.1 Motion of a conductor in a magnetic field

❖ Methods of Linking Flux

The induction of emf requires a conductor, a magnetic field and linking or cutting of flux by the conductor. The linking of magnetic field by the conductor can occur in three ways:

(i) Moving conductor and stationary permanent magnet or dc electromagnet. This configuration is used in all dynamos, generators and motors.

(ii) Moving dc electromagnet and stationary conductor. This configuration is used in large ac generators and motor

(iii) Stationary conductor, stationary electromagnet and variation of flux by feeding alternating current to the magnet. This configuration is used in transformers.

❖ **Motional EMF (Dynamically Induced EMF or Speed EMF)**

Figure 1.2 shows three conductors "a", "b", "c", *moving* in a magnetic field of flux density "B" in the directions indicated by arrow. Conductor "a" *is* moving in a direction perpendicular to its length and perpendicular to the flux lines. Therefore it cuts the lines of force and a motional emf is induced in it. Let the conductor move by a distance dx in a time dt. If the length of conductor is l, the area swept by the conductor is l dx. Then change in flux linking the coil

$$= d\varphi = B.\,l\,.\,dx$$

Since there is only one conductor

$$e = \frac{d\lambda}{dt} = \frac{N d\emptyset}{dt} = \frac{B.l.dx}{dt}$$

Since $\frac{dx}{dt} = v$ *i.e* velocity of the conductor

$$e = Blv \qquad (1.2)$$

where e = emf induced, volts
B = flux density, tesla
v = velocity of conductor, metres/second
l = length of conductor, metres.

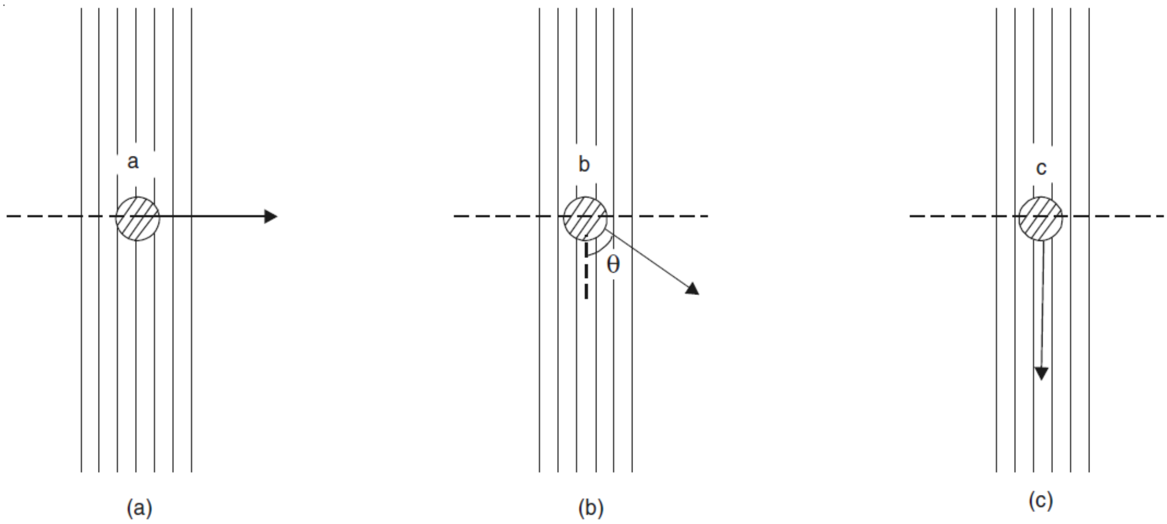


Fig. 1.2 Motion of a conductor in a magnetic field.

The motion of conductor b (Fig. 1.2b) is at an angle θ to the direction of the field. If the conductor moves by a distance dx, the component of distance travelled at right angles to the field is (dx sinθ) and, proceeding as above, the induced emf is

$$e = Bl\,v\,\sin\theta \text{ volts} \qquad (1.3)$$

Equation (1.3) includes Eq. (1.2) because when θ = 90°, the two equations become identical. In Fig. 1.2 (*c*) the motion of conductor *c* is parallel to the field. Therefore, in

this case, no flux is cut, θ is zero and induced emf is also zero. Dynamically induced emf is also known as speed emf or motional emf or rotational emf.

Equation (1.2) can also be written in a more general vectorial form:

The force F on a particle of charge Q moving with a velocity v in a magnetic field B is

$$F=Q(vxB) \tag{1.4}$$

Dividing F by Q we get the force per unit charge, *i.e.* electric field E, as

$$E = \frac{F}{Q} = v \times B \text{ volts/sec} \tag{1.5}$$

The electric field E is in a direction normal to the plane containing v and B. If the charged particle is one of the many electrons in a conductor moving across the magnetic field, the emf e between the end points of conductor is line integral of electric field E, or

$$e=\oint E.dl=\oint (vXB)dl \tag{1.6}$$

where e = emf induced, volts

E = electric field, volts/m

dl = elemental length of conductor, m

v = velocity of conductor, metres/second

B = flux density, tesla.

Eq. (1.6) is the same as Eq. (1.3), but written in a more general form. If v, B and dl are mutually perpendicular, Eq. (1.6) reduces to Eq. (1.2).

- **Statically Induced EMF (or Transformer EMF)**

Statically induced emf (also known as transformer emf) is induced by variation of flux. It may be (*a*) mutually induced or (*b*) self-induced.

A mutually induced emf is set up in a coil whenever the flux produced by a neighbouring coil changes. However, if a single coil carries alternating current, its flux will follow the changes in the current. This change in flux will induce an emf known as self-induced emf in the coil, the word 'self' signifying that it is induced due to a change in its own current. The magnitude of statically induced emf may be found by the use of Eq. (1.1). It is also known as transformer emf, since it is induced in the windings of a transformer.

Eq. (1.1) can also be put in a more general form. The total flux linkages λ of a coil is equal to the integral of the normal component of flux density B over the surface bounded by the coil, or

$$\lambda = \iint \boldsymbol{B.ds} \tag{1.7}$$

The surface over which the integration is carried out is the surface bounded by the periphery of the coil. Thus, induced emf

$$e = \frac{d\lambda}{dt} = \frac{d}{dt}\iint B.ds$$

or

$$e = \frac{d}{dt}\int_s \; B.ds \tag{1.8}$$

$$e = \int_s \; \frac{dB}{dt}.ds \tag{1.9}$$

When the coil is stationary or fixed

Where e = emf induced, volts
B = flux density, tesla
ds = element of area, m^2
t = time, seconds.

- **General Case of Induction**

Equation (1.6) gives the speed emf, while Eq. (1.9) gives the transformer emf. When flux is changing with time and relative motion between coil (or conductor) and flux also exists, both these emfs are induced and the total induced emf e is

$$e = \oint(vXB)dl - \int_s \; \frac{dB}{dt}.ds \tag{1.10}$$

The first term in Eq. (1.10) is the speed emf and line integral is taken around the coil or conductor. The second term is the transformer emf and the surface integral is taken over the entire surface bounded by the coil. In a particular case, either or both of these emfs may be present. The negative sign in Eq.(1.10) in due to Lenz's law.

λ= flux linkage, weber turns

N = number of turns in the winding

Φ = flux, webers

t = time, seconds.

- **Fleming's right-hand rule**

The direction (polarity) of dynamically induced emf can be determined by the following rule, known as Fleming's right hand rule.

"Hold the thumb, the first and the second (or middle) finger of the right hand at right angles to each other. If the thumb points to the direction of motion and first finger to the direction of the field, the second finger will point in the direction of induced emf" (i.e. the second finger will point to the positive terminal of emf or will indicate the

direction of current flow if the ends of the conductor are connected to external circuit).

- **Force on current carrying conductor in a magnetic field**

Figure 1.3 (*a*) shows a conductor lying in a magnetic field of flux density *B*. The conductor is carrying a current (entering the page). This current sets up a flux in clockwise direction. The external field is in a downward direction. As seen in Fig. 1.3 (*a*) the field of the conductor assists the external field on the right hand side of the conductor and opposes it on the left hand side. This produces a force on the conductor towards left. If the direction of current is reversed (Fig. 1.3 (*b*)), the flux due to this current assumes counter-clockwise direction and the force on the conductor is towards right. In both cases, the force is in a direction perpendicular to both the conductor and the field and is maximum if the conductor is at right angles to the field. The magnitude of this force is

$$F = B\ I\ L\ \textit{Newton} \tag{1.11}$$

where *B* is flux density in tesla, *I* is current is amperes and *l* is the length of conductor in metres. If the conductor is inclined at an angle θ to the magnetic field, the force is

$$F = BI\,l \sin\theta\ .\mathrm{N} \tag{1.12}$$

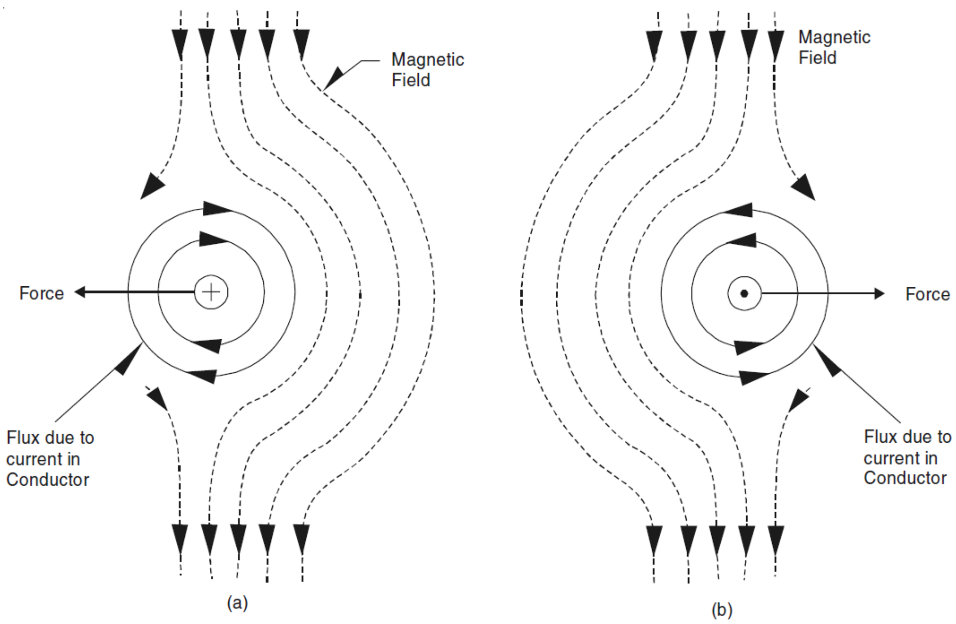


Fig. 1.3 Force on a conductor in a magnetic field (*a*) current into the page, (*b*) current out of the page.

- **Torque on a current carrying coil in a magnetic field**

Figure 1.4 shows a coil carrying *I* and lying in a magnetic field of flux density *B*. Eq (1.11) gives the force on each conductor and the total force is if the coil has N turns, the total force is

$$F = 2N\,B\,I\,l \text{ newtons}$$

The torque is acting at a radius of r metres and is given by

$$\text{Torque} = 2N\,BI\,l\,r \text{ N-m} \tag{1.13}$$

The configuration of Fig. 1.4 is the basic moving part in an electrical measuring instrument. An electric motor also works on this principle.

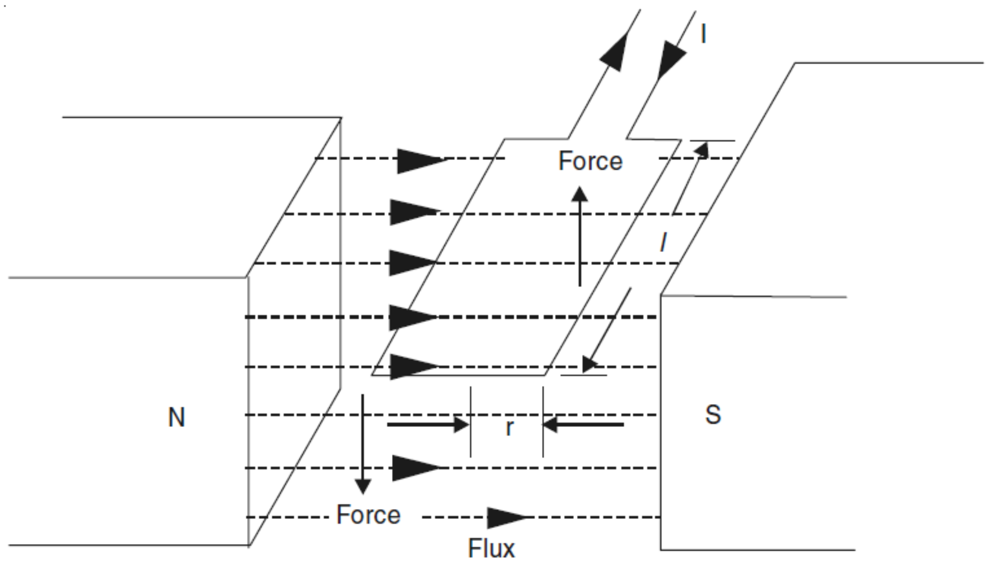


Fig. 1.4 Torque on a coil in a magnetic field

❖ **Fleming's left hand rule**

The direction of force on a current carrying conductor, situated in a magnetic field, can be found from Fleming's left hand rule:

"Hold the thumb, the first and the second (or middle) finger of the left hand at right angles to each other. If the first finger points to the direction of field and the second finger to the direction of current, the thumb will point to the direction of force or motion."

❖ **Generator and Motor action**

It is seen from *Blv* and *Bil* equations that generator and motor actions are based on the physical reactions on conductors situated in magnetic fields. When a relative motion exits between conductor and field exists, an emf is generated in the conductor and when a conductor carries current and is placed in a magnetic field, a force is exerted on the conductor. Both generator and motor actions take place simultaneously in the windings of a rotating machine. Both generators and motors have current carrying conductors in a magnetic field. Thus both torque and speed voltage are produced. Within the winding

it is not possible to distinguish between the generator and motor action without finding the direction of power flow. Constructionally a generator and motor of one category are basically identical and differ only in details necessary for its best operation for intended service. Any generator or motor can be used for energy conversion in either direction.

- ***Magnetic Drag:***

In generators, when the conductors are moved under the magnetic field, an emf is induced in the conductors according to faradays law**. (*e=Blv*)**

When the generator is loaded, armature conductors starts supplying load current to the load and at the same time, as the armature conductors are placed under the magnetic field , conductors experiences the force according to Lorentz's force equation.***(F=Bil)***

If by flemming left hand rule, if the direction of the force on the conductor is found, the developed force is acting opposite to the direction of the applied mechanical prime mover force, such a force on the armature conductor is called Magnetic drag.

i.e Armature conductor of the generator not only have voltage in them , but also force on them.

As generator converts mechanical energy into electrical energy. The torque produced, in a generator, is a counter torque (Magnetic drag) opposing rotation. The prime mover must overcome this counter torque. An increase (or decrease) in electrical power output means an increase (or decrease) in counter torque, which finally results in an increase (or decrease) in torque supplied by the prime mover to the generator.

- ***Back emf:***

In case of motor, when the current carrying conductor are placed under the magnetic field, conductor experiences the force according to lorentz's force equation (F=BIL), and the armature starts rotating.

When the armature starts rotating, the armature conductor cuts the magnetic field and hence an emf is induced in the armature conductors according to faraday law (e=Blv).

If by flemming right hand rule, if the direction of induced emf is found, induced emf is acting opposite to the applied emf, and such an emf is called is called back emf.

i.e, the armature conductors of a motor not only have force on them, but they do have voltage in them , such a voltage is called back emf.

A motor converts electrical energy into mechanical energy. The speed voltage generated in the conductors is a counter or back emf, which opposes the applied voltage. It is through the mechanism of back emf that a motor adjusts its electrical input to meet an increase (or decrease) in mechanical load on the shaft.

❖ CLASSIFICATION OF ELECTRIC MACHINES

Electric machines can be broadly classified as DC machines and AC machines. Each of these can be further classified into different categories.

- **DC Machines**

They can be further classified as dc generators and dc motors. The dc generator converts mechanical energy into electrical energy (dc). The prime mover (*i.e.* source of mechanical energy) provides rotary motion to the conductor. This relative motion between conductors and the magnetic field causes an emf to be induced in the conductors and dc is generated. A dc motor converts electrical energy (dc) into mechanical energy. The electrical energy to the motor is supplied from a dc source and the mechanical energy produced by the motor is used to drive a mechanical load (e.g. fan, lathe, etc.)

- **AC Machines**

They can be classified as transformers, synchronous machines, induction machines, AC commutator machines and special machines.

(a) Transformers: A transformer is not an electro-mechanical device. It converts ac electrical energy at one voltage to ac electrical energy at another voltage. Transformers are widely used in electrical power systems, electronic, instrumentation and control circuits.

(*b*) *Synchronous machines*: In a synchronous machine, the rotor moves at a speed which bears a constant relationship to the frequency of ac. This speed is known as synchronous speed. They are all 3-phase machines, because ac systems are all 3-phase systems.

A synchronous generator converts mechanical energy into 3-phase ac energy. It is also known as alternator.

A synchronous motor receives electrical energy from a 3-phase ac supply and converts it into mechanical energy. It produces a continuous positive torque only at its constant synchronous speed.

(*c*) *Induction machines:* This machine derives its name from the fact that emf in the rotor is induced due to magnetic induction.

A 3-phase induction motor converts 3-phase ac energy into mechanical energy. They are very widely used in small scale, medium and large industries, workshops, etc.

A single-phase induction motor converts single-phase ac into mechanical energy. They are very widely used in household devices, viz. fans, refrigerators, washing machines, etc.

An induction generator can convert mechanical energy into 3-phase ac energy. However, it is not used due to certain limitations.

(*d*) *AC commutator machines:* An ac commutator motor derives its name from the fact that it has a commutator. These motors have special characteristics and are used for special applications. They can be 3-phase motors or single-phase motors.

(*e*) *Special machines:* These motors have special constructional features and are used for special applications, e.g. computer peripheral devices, line printers, control circuits, etc.

3-phase Induction Machines

1. The induction machine is basically a rotating machine. It is either to convert mechanical energy to electrical energy (Induction generator) and to convert electrical energy to mechanical energy (Induction motor)
2. Constructionally there is no difference between induction generator and induction motor, the same machine can be used as either generator or a motor
   (i) If the Input is electrical energy, then it work as an induction motor
   (ii) If the input is mechanical energy , then it work as an induction generator
3. Induction machines can be operated in two modes
   (i) Motoring mode –It is possible , when Nr < Ns
   (ii) Generating mode- It is possible , when Nr > Ns

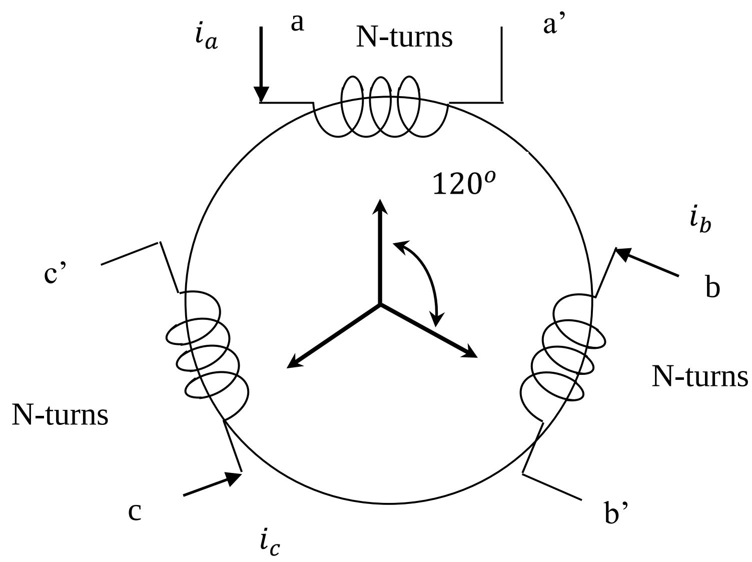
   Where Nr is the rotor speed and Ns is the synchronous speed
4. If Nr=Ns, No operation is present, so induction machines are also called as asynchronous machines

Features:

- ❖ Induction machines is basically asynchronous machine
- ❖ Induction machine is similar to transformer.
- ❖ In induction machine the two windings are Stator winding & Rotor winding
- ❖ Induction machine is singly excited machine as like as Transformer.
- ❖ Induction machine and transformer both are operated on principle is mutual induction principle.
- ❖ Induction machine is a transformer with a rotating short circuited secondary.
- ❖ The phasor diagram and equivalent circuit of 3-ϕ induction motor are almost similar to those in a transformer.
- ❖ In Induction motor, the magnetizing current is 30-50% of rated current.
- ❖ Induction machine is a variable frequency machine (i.e. slip frequency)
- ❖ This machine is electro – mechanical energy conversion machine.
- ❖ In Induction machine magnetic circuit is discontinuous magnetic circuit or composite magnetic circuit. (Air gap is the magnetic path between stator & rotor)
- ❖ Reluctance offered to the flux is high as compared with transformer due to air gap.
- ❖ Induction motor is just similar to D.C shunt motor and has D.C shunt motor type characteristics.(D.C shunt motor is replaced by Induction motor)
- ❖ Speed control of Induction machine is very difficult.
- ❖ Mechanical power output $P = \frac{2\pi NT}{60}$, If $N\downarrow \rightarrow P\downarrow$

- **Conditions To Be Satisfied To Get The Rotating Nature Of Magnetic Field – Rotating Magnetic Field- 3 Phase Systems**

1. The three phase winding must be physically displaced by 120^0 electrical in space

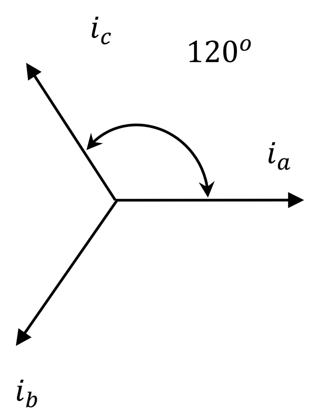


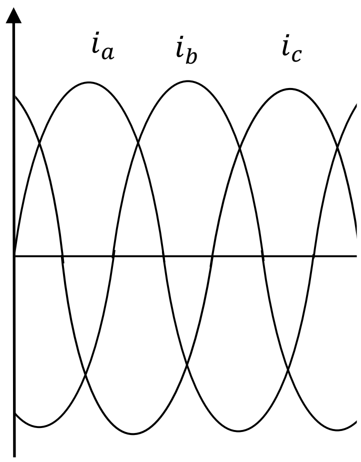
The mathematical representation of the three phase stator winding are given below

$$a - phase \rightarrow N\cos\theta$$
$$b - phase \rightarrow N\cos(\theta - 120^0)$$
$$c - phase \rightarrow N\cos(\theta - 240^0)$$

where N= Number of turns/phase ; θ= Space angle

2. The three phase currents allowed to flow through the above three windings. These currents must be time displaced by 120^o electrical





The mathematical representation of stator currents are given by

$$a - phase\ current \rightarrow i_m \cos \omega t$$

$$b - phase\ current \rightarrow i_m\, (\cos \omega t - 120^0)$$

$$c - phase\ current \rightarrow i_m\, (\cos \omega t - 240^0)$$

where i_m denotes their peak value and ω is the supply radian frequency. When the three phase a, b and C winding are excited by the three phase balanced currents, these currents set up three pulsating m .m. f waves in the air gap. These m.m f s are directed along the magnetic axis of phases a, b and c axis

3. The mmf produced by phase a winding and phase a current is given by

$$\Im_a = (N \cos \theta) \times (i_m \cos \omega t)$$

$$\Im_a = N\, i_m \cos \theta \cos \omega t$$

$$\Im_a = f_m \cos \theta \cos \omega t$$

Where f_m the peak is value of mmf due to phase a winding and phase a currents

Observation 1: The mmf due to phase a winding and phase a currents is stationary alternating with an amplitude f_m along a-axis

The mmf produced by phase b winding and phase b current, and phase c and phase c current is given by

$$\Im_b = f_m \cos(\theta - 120^0)\, \cos(\omega t - 120^0)$$

$$\Im_c = f_m \cos(\theta - 240^0)\, \cos(\omega t - 240^0)$$

Observation 2: The mmf due to other phase winding and other currents is also stationary alternating with an amplitude f_m along their respective axis

The pulsating mmf are given by

For phase a,

$$\Im_a = \frac{1}{2} f_m \cos(\theta - \omega t) + \frac{1}{2} f_m \cos(\theta + \omega t)$$

For phase b

$$\Im_b = \frac{1}{2} f_m \cos(\theta - 120^0 - \omega t + 120^0) + \frac{1}{2} f_m \cos(\theta - 120^0 + \omega t + 120^0)$$

$$\Im_b = \frac{1}{2} f_m \cos(\theta - \omega t) + \frac{1}{2} f_m \cos(\theta + \omega t - 240^0)$$

Phase c,

$$\Im_c = \frac{1}{2} f_m \cos(\theta - 240^0 - \omega t + 240^0) + \frac{1}{2} f_m \cos(\theta - 240^0 + \omega t - 240^0)$$

Resultant mmf $\Im_R$ (θ, t) is obtained by

$$\boldsymbol{\Im_R\ (\theta, t) = \frac{3}{2} f_m cos(\theta - \omega t)}$$

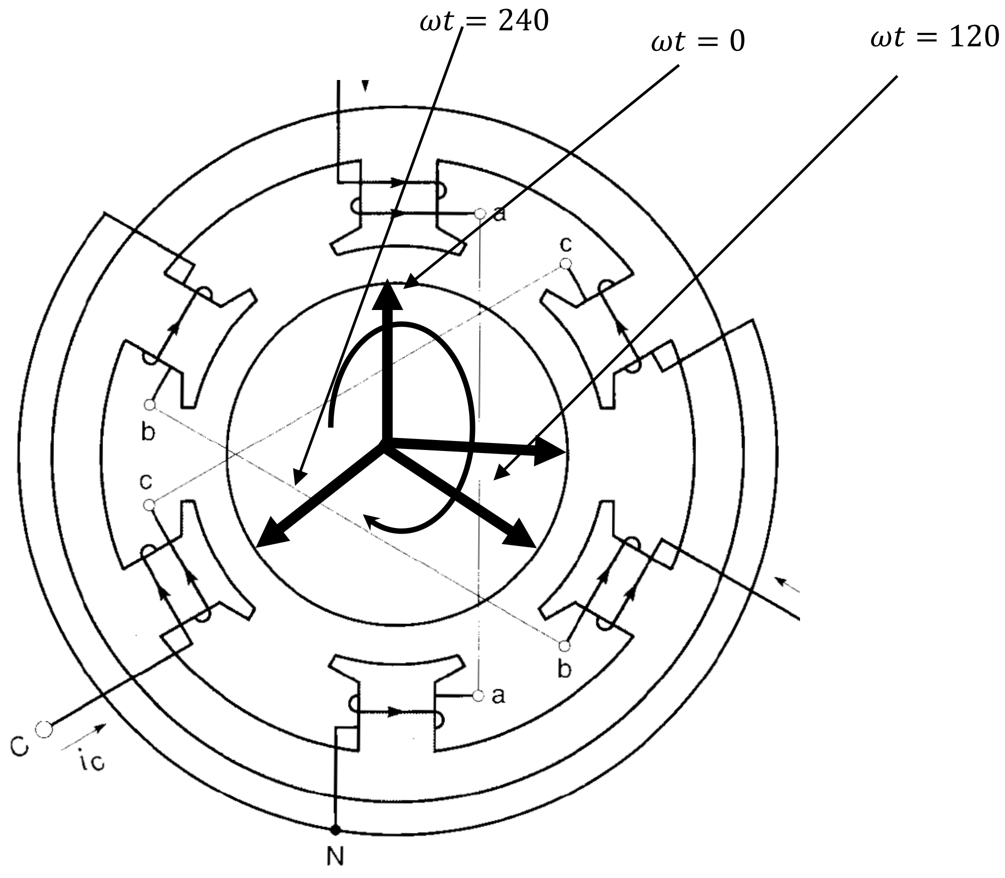
For

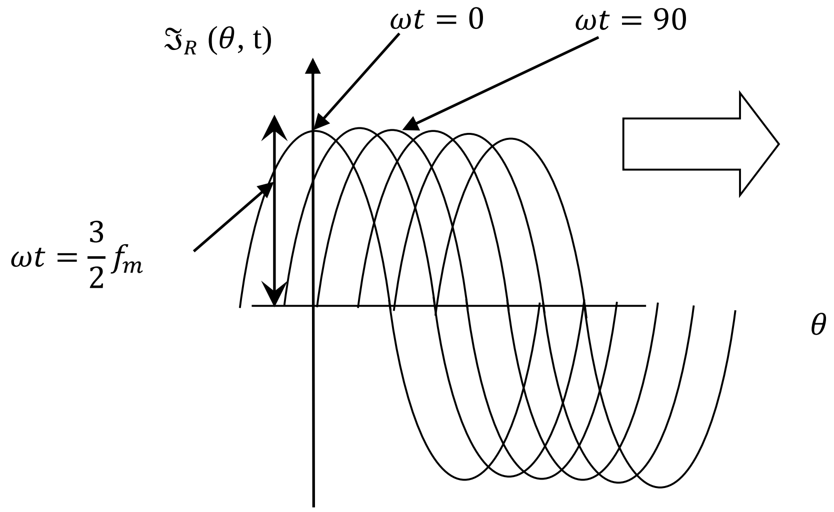
$\omega t = 0;$ $\Im_R$ (θ, t) = $\frac{3}{2} f_m \cos\theta$

$\omega t = 90;$ $\Im_R$ (θ, t) = $\frac{3}{2} f_m \cos(\theta - 90)$

$\omega t = 120;$ $\Im_R$ (θ, t) = $\frac{3}{2} f_m \cos(\theta - 120)$

$\omega t = 240;$ $\Im_R$ (θ, t) = $\frac{3}{2} f_m \cos(\theta - 240)$





The mmf wave is of constant amplitude $\frac{3}{2}$ $\boldsymbol{f_m}$ and is traveling in the position θ direction at a speed determined by time angular frequency "ω".

For a p – pole machine the synchronous speed

$$\omega_m = \frac{2}{p}\,\omega = \frac{4\pi f}{p}\ \text{rad/sec}$$

$$n_s = \frac{2f}{p}\ \text{rps}$$

$$N_s = \frac{120f}{p}\ rpm, \text{ this particular speed is called synchronous speed}$$

When $\omega t = 0^0$, $\theta = 0^0$ current in phase "a" is maximum and peak of traveling wave $\frac{3}{2}f_m$ is along axis of phase – a.

$\omega t = 120^0$, i_b is max to peak of traveling mmf wave along axis of phase – b.

$$\Im_R\ (\theta, t) = \frac{3}{2}f_m \cos(120–120) = \frac{3}{2}f_m$$

Parallel when $\omega t = 240^0$, $\theta = 240^0$ peak of traveling mmf wave is aligned along phase 'c'.

$\therefore$ The peak of rotating mmf wave travels from phase a → b → c (*i.e.* clock wise)

Conclusions:

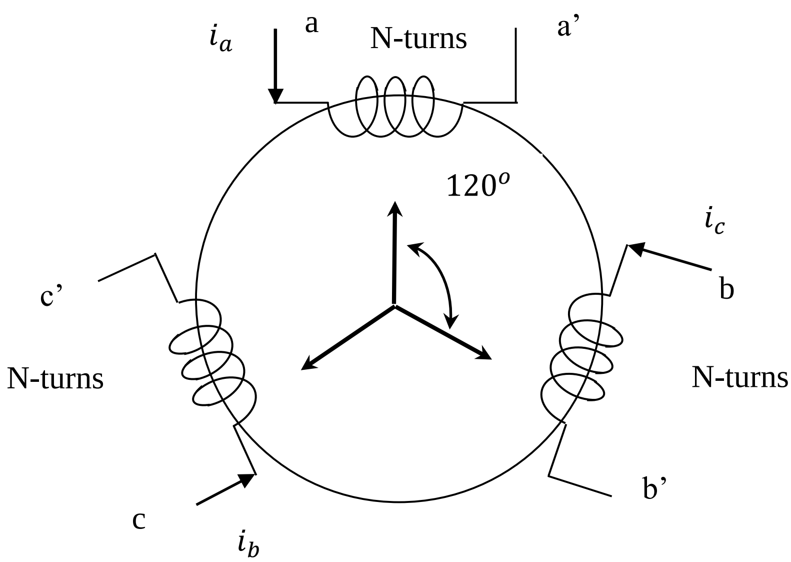
(1) Whenever 3-phase windings are physically displaced by 120^0 degrees electrically and are being fed from a 3 –phase currents which are time displaced by 120^0 degrees electrically. The we have three mmf produced in the air gap which are stationary alternating with an amplitude of f_m along their own axis and the resultant mmf due to 3

phase individual mmf has a constant amplitude of $\frac{3}{2} f_m$, where f_m is the maximum mmf due to any phase and rotates with a speed called synchronous speed given by $\frac{120f}{p}$ As the resultant mmf wave rotates at synchronous speed, the flux wave due to this mmf also rotates at synchronous speed in the air gap and this type of magnetic field is called ***rotating magnetic field.***

(2) In 3-phase transformers even though the currents in the windings are time displaced by 120 degrees, the windings are not physically displaced by 120 degrees in the space. That's why rotating nature of magnetic field is not present in 3 phase transformers**.**

❖ **Conditions to be satisfied to reverse the direction of Rotating Magnetic Field**

1. The three phase winding must be physically displaced by 120^0 electrical in space



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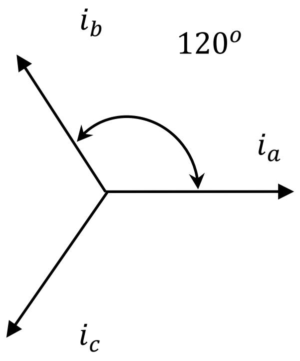
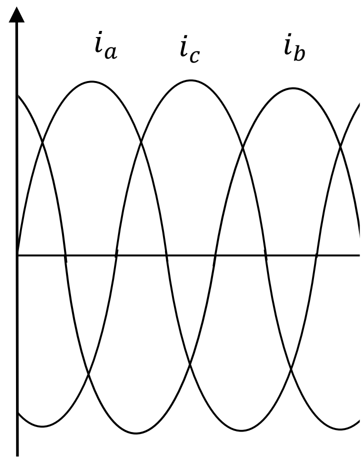
$$b - phase \rightarrow N \cos(\theta - 120^0)$$

$$c - phase \rightarrow N \cos(\theta - 240^0)$$

where N= Number of turns/phase ; θ= Space angle

2. The three phase currents allowed to flow through the above three windings. These currents must be time displaced by 120^o electrical





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$$c - phase\ current \rightarrow i_m\ (\cos \omega t - 240^0)$$

where i_m denotes their peak value and ω is the supply radian frequency. When the three phase a, b and c winding are excited by the three phase balanced currents, these currents set up three pulsating m .m. f waves in the air gap. These m.m f s are directed along the magnetic axis of phases a, b and c axis

3. The mmf produced by phase a winding and phase a current is given by

$$\Im_a = (N \cos \theta) \times (i_m \cos \omega t)$$

$$\Im_a = N\, i_m \cos \theta \cos \omega t$$

$$\Im_a = f_m \cos \theta \cos \omega t$$

Where f_m the peak is value of mmf due to phase a winding and phase a currents

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The mmf produced by phase b winding and phase c current, and phase c and phase b current is given by

$$\Im_b = f_m \cos(\theta - 120^0)\cos(\omega t - 240^0)$$

$$\Im_c = f_m \cos(\theta - 240^0)\cos(\omega t - 120^0)$$

Observation 2: The mmf due to other phase windings and other currents is also stationary alternating with an amplitude f_m along their respective axis

The pulsating mmf are given by

For phase a,

$$\Im_a = \frac{1}{2} f_m \cos(\theta - \omega t) + \frac{1}{2} f_m \cos(\theta + \omega t)$$

Resultant mmf $\Im_c$ (θ, t) is obtained by

$$\boldsymbol{\Im_R(\theta, t) = \frac{3}{2} f_m \cos(\theta + \omega t)}$$

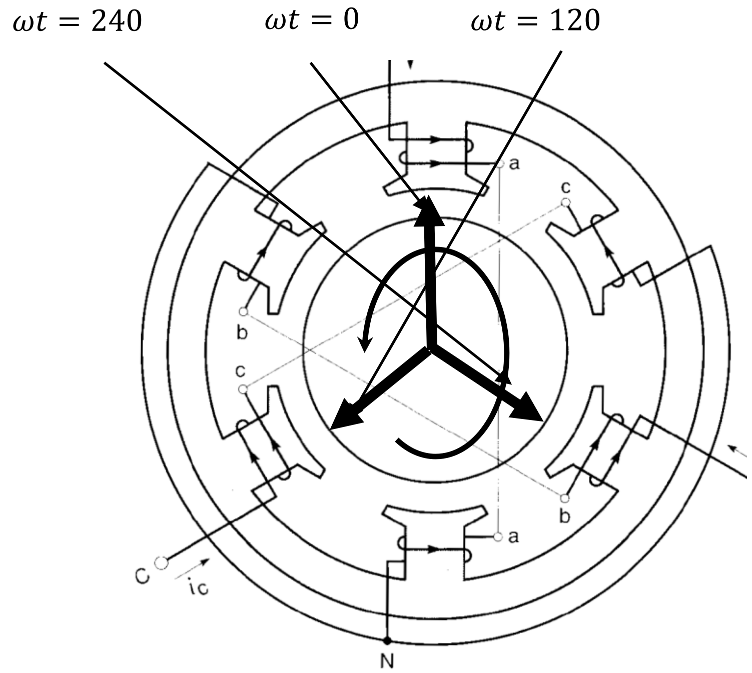
For

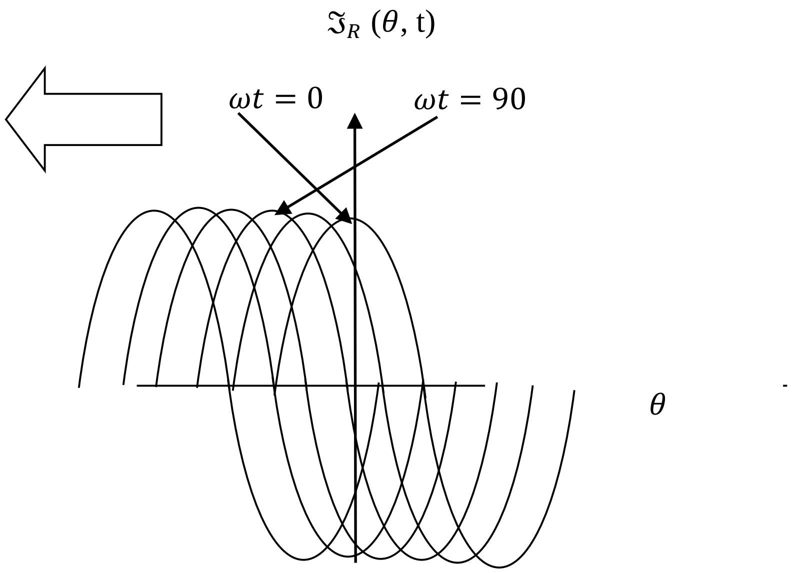
$\omega t = 0;$ $\Im_R(\theta, t) = \frac{3}{2} f_m \cos\theta$

$\omega t = 90;$ $\Im_R(\theta, t) = \frac{3}{2} f_m \cos(\theta + 90)$

$\omega t = 120;$ $\Im_R(\theta, t) = \frac{3}{2} f_m \cos(\theta + 120)$

$\omega t = 240;$ $\Im_R(\theta, t) = \frac{3}{2} f_m \cos(\theta + 240)$





The mmf wave is of constant amplitude $\frac{3}{2}$ f_m and is traveling in the position θ direction at a speed determined by time angular frequencyω.

For a p – pole machine the synchronous speed

$$\omega_m = \frac{2}{p}\omega = \frac{4\pi f}{p} \text{ rad/sec}$$

$$n_s = \frac{2f}{p} \text{rps}$$

$$N_s = \frac{120f}{p} \text{rpm, this particular speed is called synchronous speed}$$

When $\omega t = 0^0$, $\theta = 0^0$ current in phase a is maximum and peak of traveling wave $\frac{3}{2}f_m$ is along axis of phase – a.

∴ The peak of rotating mmf wave travels from phase a → c → b (*ie*. Anti- clock wise)

Note: To reverse the direction of the rotating magnetic field interchange any two terminal with supply mains, not all the three terminals

❖ Generalized Conditions To Be Satisfied To Get Rotating Magnetic Fields with "m" phase systems

1. m > 2 (Minimum number is -3)
2. m-phase windings must be physically displaced by

$$\frac{2\pi}{m} \text{ radians (electrically)} - \text{space angel } \theta$$

3. m-phase currents must be time displaced by

$$\frac{2\pi}{m} \text{ radians (electrically)} - \text{time angle } \omega t$$

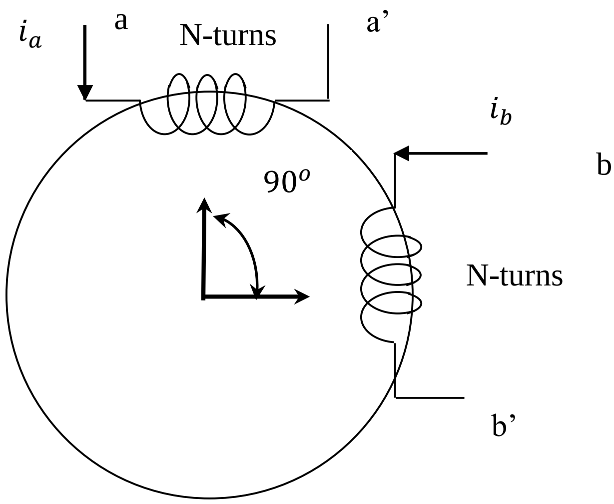
4. when these ***m-phase currents*** with a time angle of $\frac{2\pi}{m}$ radians (electrically) are allowed to flow through the ***m-phase windings*** which are physically spaced with a space angle of $\frac{2\pi}{m}$ radians (electrically), then the resultant mmf due to "m" phase mmf has a constant amplitude of $\frac{m}{2}$ times maximum mmf due to any phase and rotates with a speed given by $\frac{120f}{p}$ called synchronous speed given by

$$\Im_R(\theta, t) = \frac{m}{2} f_m \cos(\theta - \omega t)$$

and flux produces by such travelling mmf wave will be a ***rotating flux wave.***

❖ Generalized Conditions to Be Satisfied To Get Rotating Magnetic Fields With "2" Phase Systems

1. The two phase winding must be physically displaced by 90^0 electrical in space



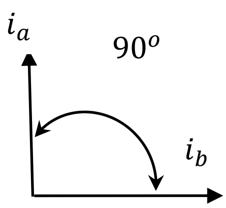
The mathematical representation of the two phase stator winding are given below

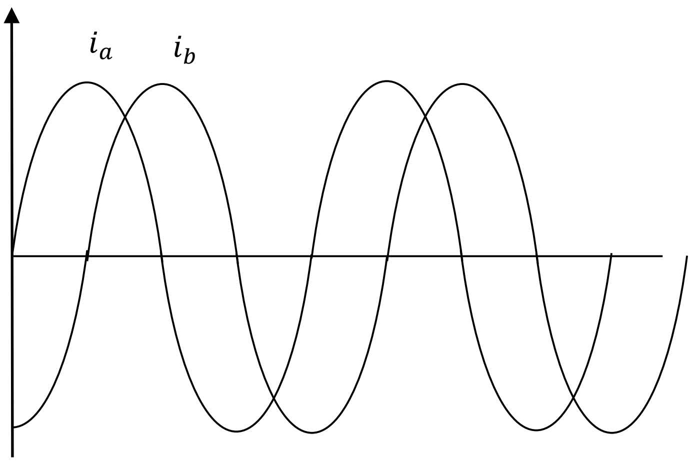
$$a - phase \rightarrow N\cos\theta$$

$$b - phase \rightarrow N\cos(\theta - 90^0)$$

where N= Number of turns/phase ; θ= Space angle

2. The two phase currents allowed to flow through the above two windings. These currents must be time displaced by 90^o electrical





The mathematical representation of stator currents are given by

$$a - phase\ current \rightarrow i_m \cos \omega t$$

$$b - phase\ current \rightarrow i_m\,(\cos \omega t - 90^0)$$

where i_m denotes their peak value and ω is the supply radian frequency. When the two phases "a" and "b" are excited by the two phase balanced currents, these currents set up two pulsating m .m. f waves in the air gap. These m.m f s are directed along the magnetic axis of phases "a" and "b" axis

3. The mmf produced by phase a winding and phase a current is given by

$$\Im_a = (N \cos \theta) \times (i_m \cos \omega t)$$

$$\Im_a = N\, i_m \cos \theta \cos \omega t$$

$$\Im_a = f_m \cos \theta \cos \omega t$$

Where f_m the peak is value of mmf due to phase a winding and phase a currents

Observation 1: The mmf due to phase a winding and phase a currents is stationary alternating with an amplitude f_m along a-axis

The mmf produced by phase b winding and phase c current, and phase c and phase b current is given by

$$\Im_b = f_m \cos(\theta - 90^0)\, \cos(\omega t - 90^0)$$

Observation 2: The mmf due to other phase windings and other currents is also stationary alternating with an amplitude f_m along their respective axis

The pulsating mmf are given by

For phase a,

$$\Im_a = \frac{1}{2} f_m \cos(\theta - \omega t) + \frac{1}{2} f_m \cos(\theta + \omega t)$$

Resultant mmf $\Im_c$ (θ, t) is obtained by

$$\Im_R\ (\theta, \mathrm{t}) = f_m \cos(\theta - \omega t)$$

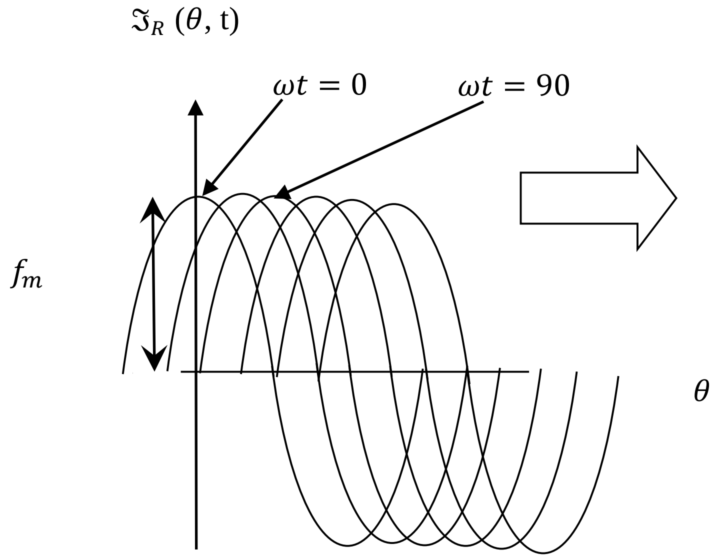
For

$\omega t = 0$; $\Im_R$ (θ, t) = $f_m \cos\theta$

$\omega t = 90$; $\Im_R$ (θ, t) = $f_m \cos(\theta - 90)$

$\omega t = 120$; $\Im_R$ (θ, t) = $f_m \cos(\theta - 120)$

$\omega t = 240$; $\Im_R$ (θ, t) = $f_m \cos(\theta - 240)$



The mmf wave is of constant amplitude f_m and is traveling in the position θ direction at a speed determined by time angular frequencyω.

For a p – pole machine the synchronous speed

$$\omega_m = \frac{2}{p}\omega = \frac{4\pi f}{p} \text{ rad/sec}$$

$$n_s = \frac{2f}{p} \text{ rps}$$

$N_s = \dfrac{120f}{p}$ rpm, this particular speed is called synchronous speed

When ωt = 0^0, θ= 0^0 current in phase "a" is maximum and peak of traveling wave f_m is along axis of phase – a.

ωt = 90^0, i_b is max to peak of traveling mmf wave along axis of phase – b.

$\Im_R$ (θ, t) = $f_m$cos (90–90) = f_m

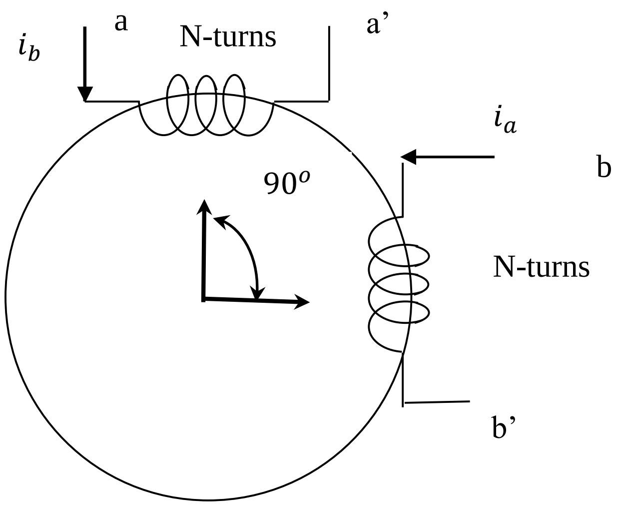
∴ The peak of rotating mmf wave travels from phase a → b → a (i.e. clock wise)

Conclusions: Whenever 2-phase windings are physically displaced by 90^0 degrees electrically and are being fed from a 2 –phase currents which are time displaced by 90^0 degrees electrically, Then we have two mmf produced in the air gap which are stationary alternating with an amplitude of f_m along their own axis and the resultant mmf due to 2 phase individual mmf has a constant amplitude of f_m , where f_m is the maximum mmf due to any phase and rotates with a speed called synchronous speed given by $\frac{120f}{p}$

As the resultant mmf wave rotates at synchronous speed, the flux wave due to this mmf also rotates at synchronous speed in the air gap and this type of magnetic field is called ***rotating magnetic field.***

- **Conditions to reverse the direction of rotating magnetic fields-2 phase systems**

1. The two phase winding must be physically displaced by 90^0 electrical in space



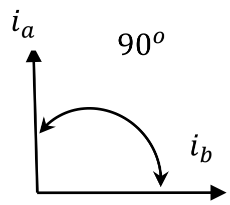
The mathematical representation of the two phase stator winding are given below

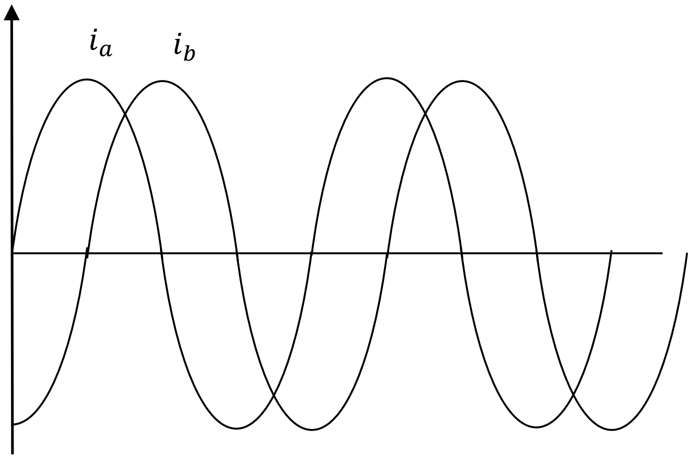
$$a - phase \rightarrow N\cos\theta$$

$$b - phase \rightarrow N\cos(\theta - 90^0)$$

where N= Number of turns/phase ; θ= Space angle

2. The two phase currents allowed to flow through the above two windings. These currents must be time displaced by 90^o electrical





The mathematical representation of stator currents are given by

$$a - phase\ current \rightarrow i_m \cos \omega t$$

$$b - phase\ current \rightarrow i_m (\cos \omega t - 90^0)$$

where i_m denotes their peak value and ω is the supply radian frequency. When the two phase “a” and “b” are excited by the two phase balanced currents, these currents set up two pulsating m .m. f waves in the air gap. These mmf s are directed along the magnetic axis of phases “a” and “b” axis

3. The mmf produced by phase a winding and phase a current is given by

$$\Im_a = (N \cos \theta) \times (i_m \cos(\omega t - 90^0))$$

$$\Im_a = N\, i_m \cos \theta \cos(\omega t - 90^0)$$

$$\Im_a = f_m \cos \theta \cos(\omega t - 90^0)$$

Where f_m the peak is value of mmf due to phase a winding and phase a currents

The mmf produced by phase b winding and phase c current, and phase c and phase b current is given by

$$\Im_b = f_m \cos(\theta - 90^0) \cos \omega t$$

Observation 1: The mmf due to other phase windings and other currents is also stationary alternating with an amplitude f_m along their respective axis

Resultant mmf $\Im_R$ (θ, t) is obtained by

$$\Im_R (\theta, t) = f_m \cos(\theta + \omega t)$$

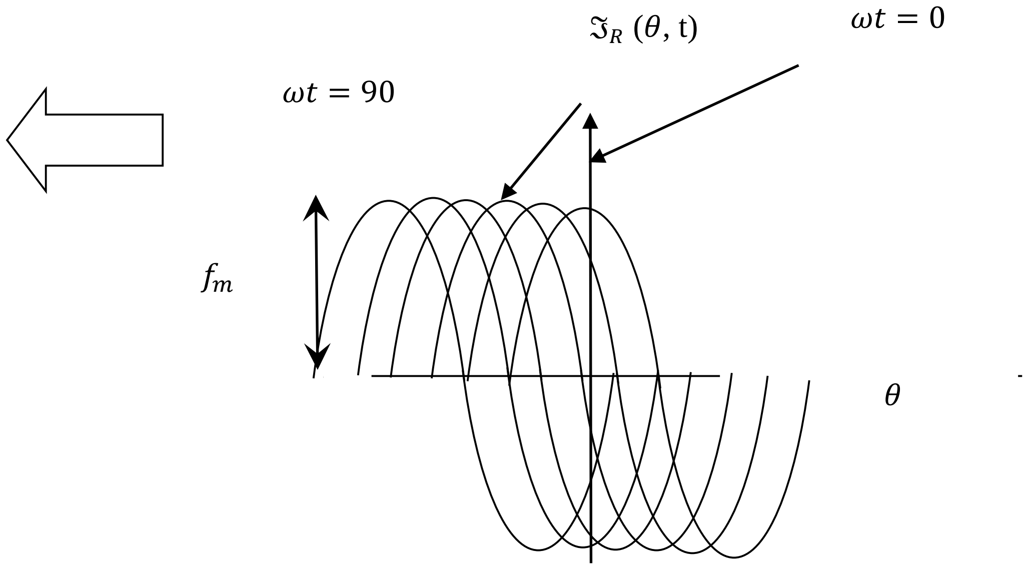
For

$\omega t = 0$; $\Im_R$ (θ, t) = $f_m \cos \theta$

$\omega t = 90$; $\Im_R$ (θ, t) = $f_m \cos(\theta + 90)$

$\omega t = 120$; $\Im_R$ (θ, t) = $f_m \cos(\theta + 120)$

$\omega t = 240$; $\Im_R$ (θ, t) = $f_m \cos(\theta + 240)$



The mmf wave is of constant amplitude f_m and is traveling in the position θ direction at a speed determined by time angular frequency ω.
For a p – pole machine the synchronous speed

$$\omega_m = \frac{2}{p}\omega = \frac{4\pi f}{p} \text{ rad/sec}$$

$$n_s = \frac{2f}{p} \text{ rps}$$

$$N_s = \frac{120f}{p} \text{ rpm, this particular speed is called synchronous speed}$$

When $\omega t = 0^0$, $\theta = 0^0$ current in phase a is maximum and peak of traveling wave f_m is along axis of phase – a.
$\therefore$ The peak of rotating mmf wave travels from phase a $\rightarrow$ -b $\rightarrow$ -a (i.e. Counter clock wise)
Note: The direction of the rotating magnetic field can be reversed by interchanging the motor terminals.

Observations

1. ***Minimum number of stationary phases required to produce the rotating magnetic field are "TWO"***
2. ***The rotating magnetic field produced by m-phase system differs only with respect to magnitude of the field, but the speed at which it rotate remains same and constant and is equal to synchronous speed.***

Construction Aspects-Induction Machines

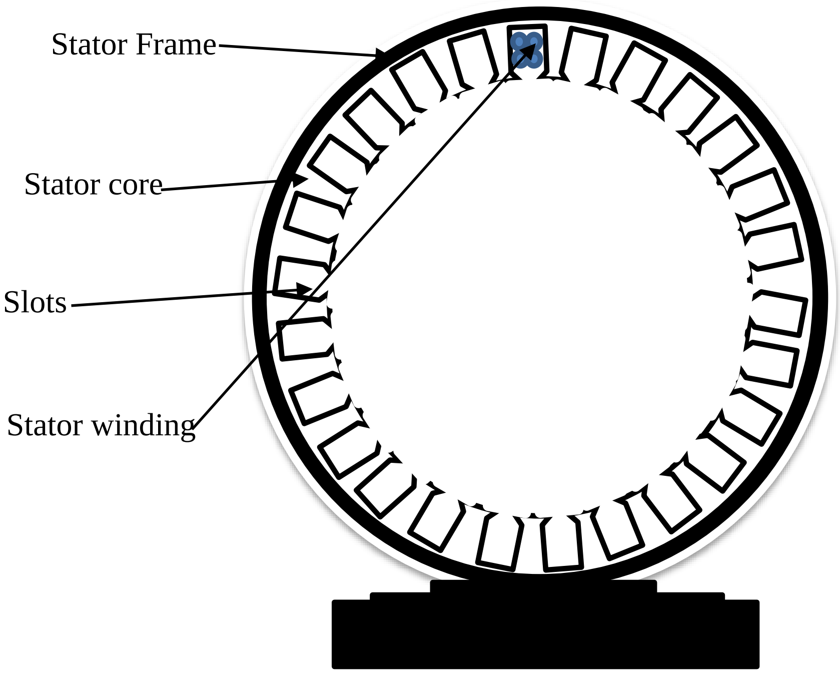
The induction machine is basically an a.c. polyphase machine connected to an a.c. power grid, either in the stator or in the rotor. The a.c. power source is, in general, three phase but it may also be single phase. In both cases the winding arrangement on the part of the machine–the primary–connected to the grid (the stator in general) should produce a travelling field in the machine air gap. This travelling field will induce voltages in conductors on the part of the machine not connected to the grid (the rotor, or the mover in general), - the secondary. If the windings on the secondary (rotor) are closed, a.c. currents occur in the rotor.

The interaction between the primary field and secondary currents produces torque from zero rotor speed onward. The rotor speed at which the rotor currents are zero is called the ideal no-load (or synchronous) speed. The rotor winding may be multiphase (wound rotors) or made of bars short circuited by end rings (cage rotors)

The induction machine has a rather uniform air gap of 0.2 to 3 mm. The largest values correspond to large power, 1 MW or more. The secondary windings may be short-circuited or connected to external impedance or to a power source of variable voltage and frequency. In the latter case however the IM works as a synchronous machine as it is doubly fed and both stator and rotor-slip frequencies are imposed

- **Stator Parts**

Let us discuss, in detail, each of them separately.



(i) Stator Frame:

Frames of electrical machines are structures in which stator core is assembled. They serve four distinct purposes.

1. They enclose the core and windings.
2. The shield the live and moving machine parts from human contact and form injury caused by instructing objects or weather exposure
3. They transmit the torque to the machine supports, and are therefore designed to withstand twisting forces & shocks.
4. They serve as ventilating housing or means of guiding the coolant into effective channels.

(ii) Stator core:

(a) The stator is the stationary part is built up of high – grade alloy steel laminations as every part of the stator core is subject to alternate changes in polarity of the magnetic field (due to its rotating nature) so hysteresis losses and eddy-current losses take place. To reduce the former, about 3-5% of silicon is added to high grade steel and to reduce the latter, a large number of thin laminations are stacked together.

(b) The stator core provides the space for housing for the three-phase stator windings and also forms the path for the rotating magnetic field. They are built up of thin sheets of thickness (called stampings or laminations) of 0.35 mm to 0.65 mm with of a special core of steel, insulated one from the other by means of paper.

(c) In case of rotating machines, CRGO steel is not preferred, and it is not required in rotating machines. In India we cannot manufacture the CRGO steel laminations. Even if CRGO steel laminations are used for stator and rotor core, we cannot reduce the overall reluctance of the magnetic circuit of the induction machine because of the presence of air gap between stator and rotor. Because of the presence of the air gap the induction machine magnetic circuit is discontinuous .As such silicon steel is used.

(d) The gap facing inner circumference of the plates have suitable slots punched out, open, semi-closed or completely closed. Normally, the stator core has semi-closed slots where the number of slots, S, is an integral multiple of 3 times the number of poles, p for which the induction motor is designed and constructed [$S = n.\ (3\ p)$], where n = 1, 2, 3 etc.

(e) The insulated stator conductors are placed in these slots. The stator conductors are connected to form a three- phase winding. The phase winding may be either star or delta connected.

(iii) Shapes of Stator Slots (Types of Slots)

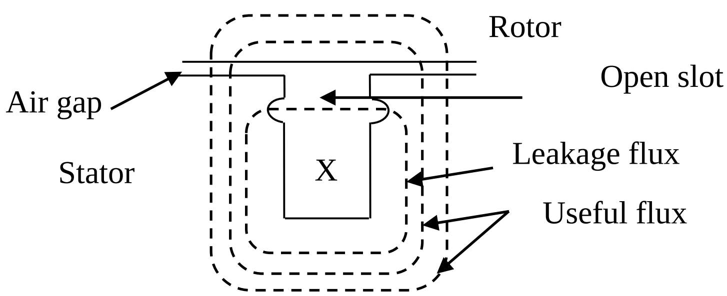
The shape of slots has an important effect upon the operating performance of the motor as well as the problem of installing the winding. In general three types of slots can be used in three phase induction machines, namely

(a) Open slots

(b) Semi-closed slots

(c) Closed slots

Open Slots



Advantages:

(i) Easy access of the winding without any problem, i.e the windings are reasonably accessible when individual coils must be replaced or serviced in the field.

(ii) Access to the former coils is easy, and winding procedure becomes easy.
Former coils are the winding coils formed and insulated completely before they are inserted in the slots.

(iii) They have less leakage reactance .Leakage reactance is less as leakage flux is less

Note:

Leakage flux: A leakage flux is a one which links stator winding or the rotor winding, but not the both. In case of a.c machines, the leakage fluxes affect the inductive reactance of the a.c winding. The performance of the inductor motor like starting torque, maximum torque, starting current etc. are dependent upon the value of the leakage reactance, where as a useful flux is a one which links both the stator and rotor winding.

Disadvantages:

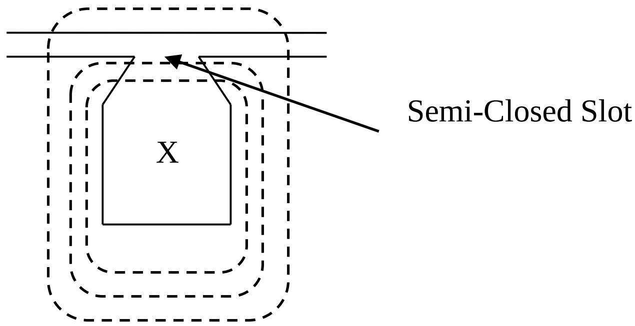
(i) Because of wide opening of slots average air gap length is more, so reluctance is more. It requires more excitation current, hence No load, full load power factor are very less.

(ii) The air gap flux distribution is non -uniform.

- If the flux density everywhere is same in the air gap, then such type of flux distribution is uniform.
- If the flux density at every two points is not same, then such type of flux distribution is not uniform, non-uniform.

Due to non-uniform flux distribution, harmonic torques is produced in the induction machines. So due to this, there is a possibility of lot of vibration and lot of noise

Semi –closed slots



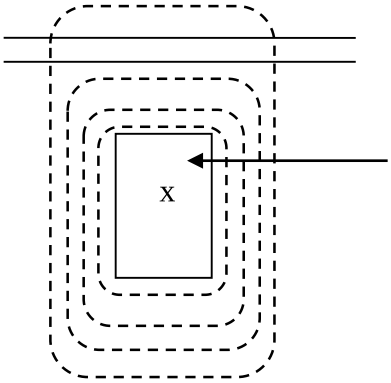
Disadvantages:

1. It is not possible to insert large former coils. It is possible to place former coil which is less than diameter opening of the semi open slots.
2. Access of slot is little bit difficult compared to open type.
3. They offer high leakage reactance to the windings

Advantages:

1. Because of narrow opening of the slots, flux distribution is uniform; as such harmonics are less the operation of the motor is smooth compared to open type.
2. Average length of the air gap is less compared to open type; as a result reluctance of the magnetic circuit is less, less magnetising current and better power factors.

Closed Slots



Disadvantages:

1. Access of winding procedure is very difficult. Access of winding is only turn by turn.
2. Access to former coils is not possible. It is not possible to place the former coils
3. Leakage reactance is very high,(leakage flux linkages are very strong)

Advantage:

1. Average air gap length is minimum. Minimum excitation current is required. As a result, improved no load and running power factors.
2. Flux distribution is uniform. No Flux harmonics are produced. So smooth operation is possible compared to other

Comparisons

Parameter	Open		Semi-closed		Closed
Magnetising Current	I_μ(open)	>	I_μ(Semi-closed)	>	I_μ(Closed)
No-load power factor	Cosφ_o(open)	<	Cosφ_o(Semi-closed)	<	Cosφ_o(Closed)
Input Power factor	Cosφ_1(open)	<	Cosφ_1(Semi-closed)	<	Cosφ_1(closed)
Leakage reactance	X_l(open)	<	X_l(Semi-closed)	<	X_l(Closed)
Maximum Torque	T_{max}(open)	>	T_{max}(Semi -closed)	>	T_{max}(Closed)
Starting Torque	T_{st}(open)	>	T_{st}(Semi-Closed)	>	T_{st}(Closed)
Harmonics Torque	T_H(open)	>	T_H(Semi-Closed)	>	T_H(Closed)

Note:

1. Among all the three types of slots semi closed type slots are preferred for induction machines as, semi-closed slots are having the partial advantages of open type and partial advantages of closed type slots.

2. Open type slots are generally preferred for synchronous and dc machines.

3. In general closed type slots are used in low hp motors, to control the starting currents, as the leakage reactance offered by closed type slots is very high compared to other types of slots.

1. Motor A has shallow and wide slots. Motor B has deeper and narrow slots. If both are 3 phase 400 V, 50 Hz, 1440 rpm induction motors, it can be concluded that(IES-1992)			
(a)	Motor A has more starting torque as compared to motor B	(b)	Motor B has more starting torque as compared to motor A
(c)	Motor A has more pull out torque as compared to motor B	(d)	Motor B has more pull out torque as compared to motor A
2	**Semi closed slots or totally closed slots are used in induction motors, essentially to**		
(a)	improve starting torque	(b)	increase pull-out torque
(c)	increase efficiency	(d)	reduce magnetizing current and improve power factor

❖ Formation of Poles

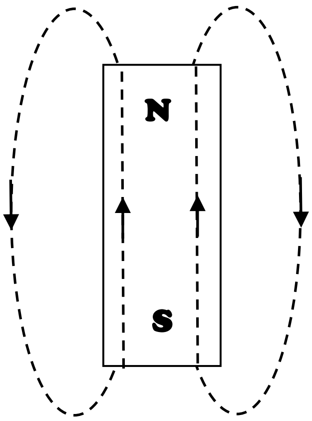
(i) Right hand thumb rule

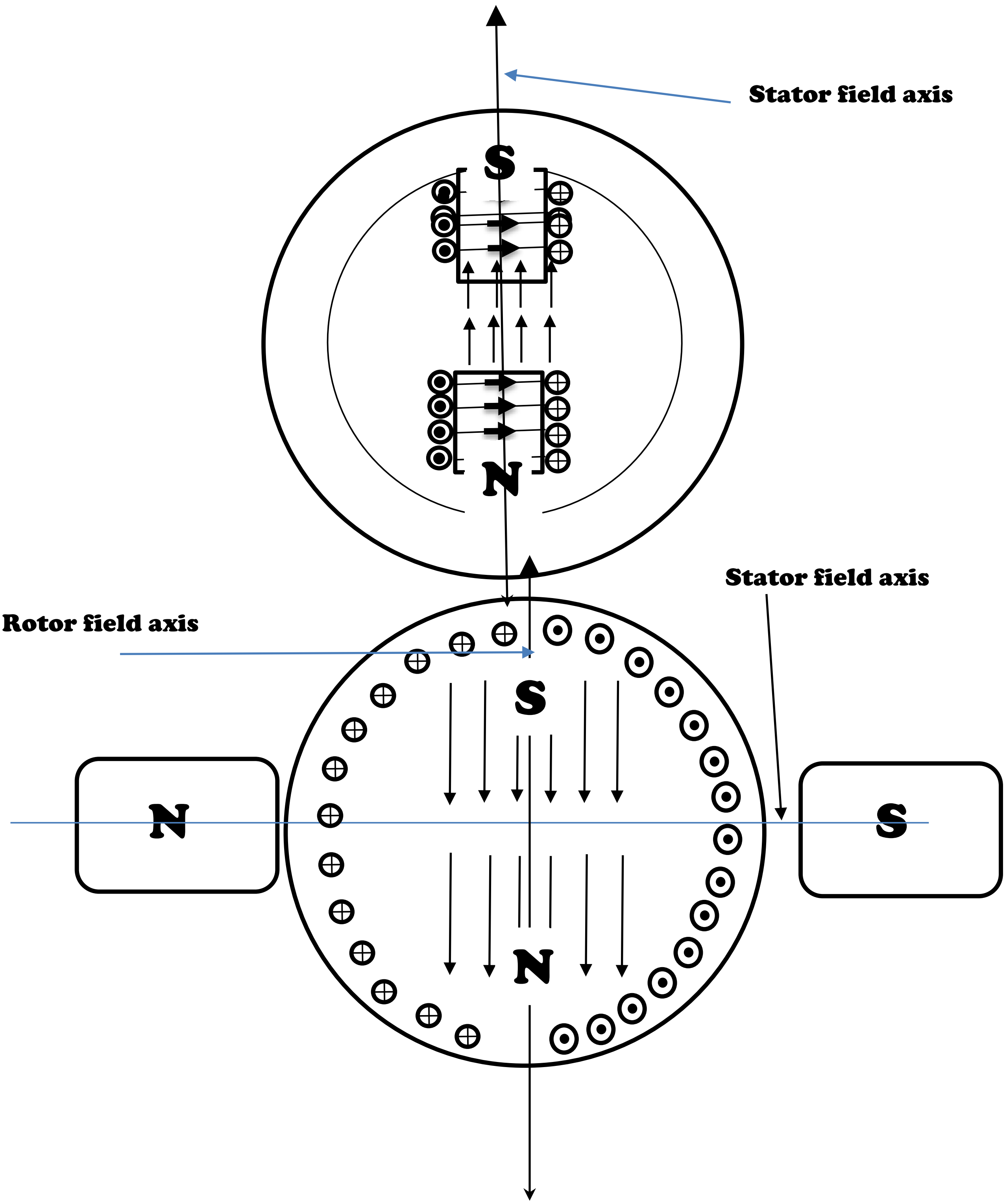
If the thumb of the right hand is place along the direction of current through a conductor, then the remaining four curled fingers gives the direction of flux lines

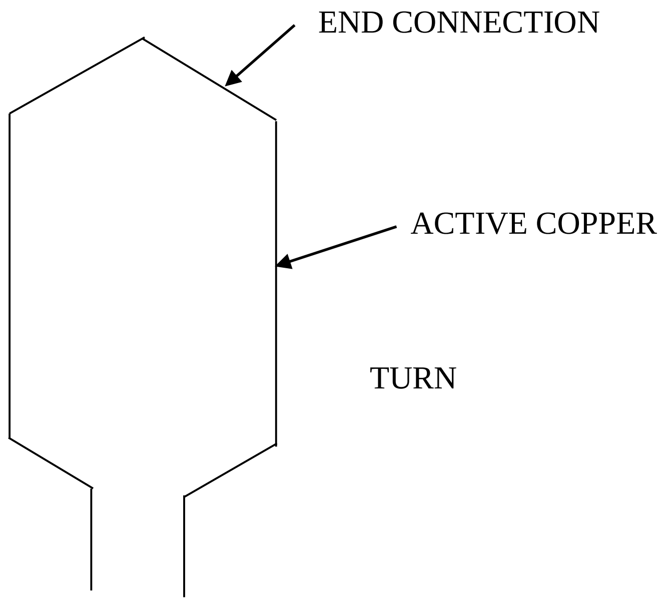
If the four fingers of the right hand are placed along the direction of current through the coil, then the thumb gives the direction of the flux line

(ii) Basic properties of a BAR Magnetic

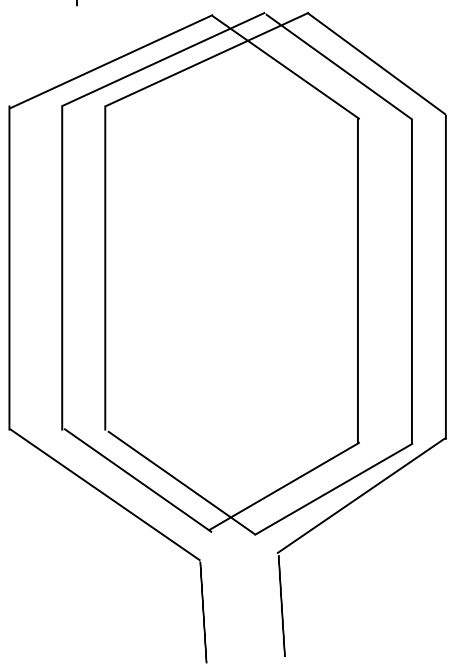
The magnetic flux lines starts from a North Pole and ends at a South Pole, and to complete the path, the flux lines travels from South Pole to North Pole internal to the magnet




Stator field axis
S
N
Stator field axis
Rotor field axis
S
N
N
S



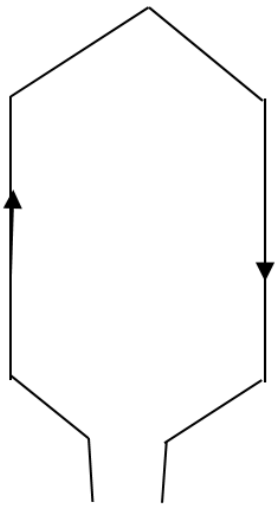
TURN

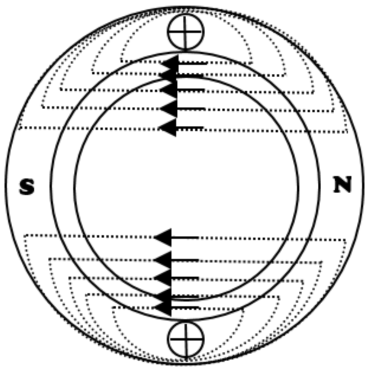


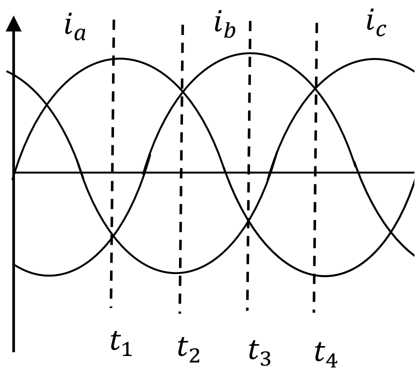
COIL

A coil may be of single turn having two conductors with end connection or multi turn with two coil sides each composed of several conductors. The active coil side (or conductor) length in which the emf is induced equals the armature length (over which the flux density is established)

The pitch of a coil is the space angle (electrical) between its two sides and must be equal to integral number of slots





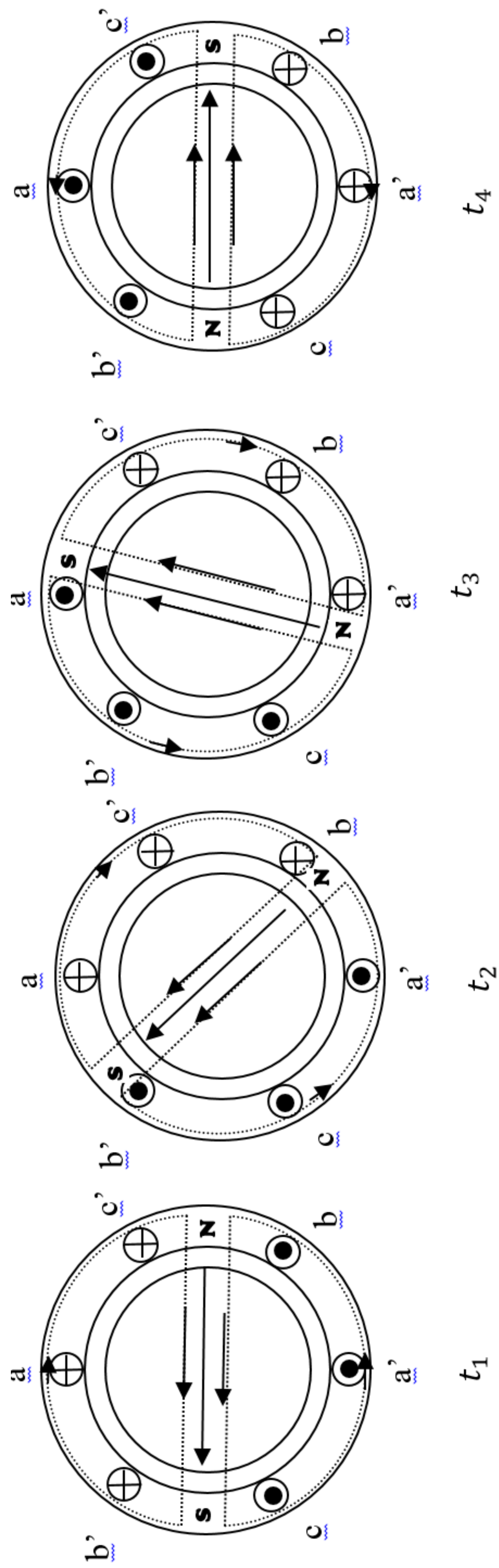


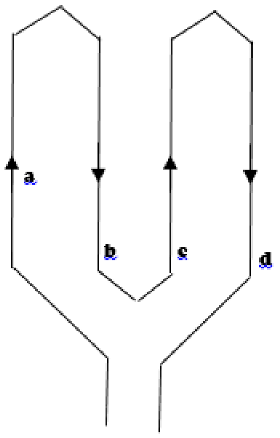
At t_1 ; i_a is positive, i_b is negative, i_c is negative

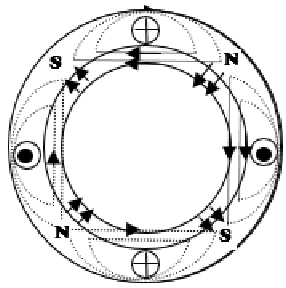
At t_2 ; i_a is positive, i_b is positive, i_c is negative

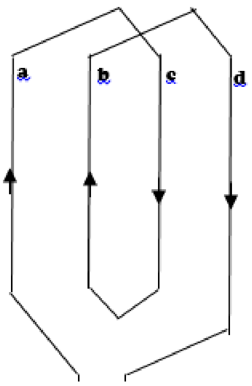
At t_3; i_a is negative, i_b is positive, i_c is negative

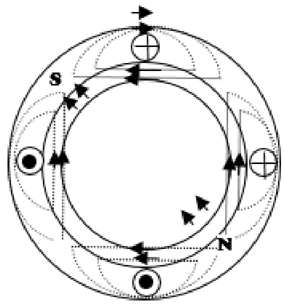
At t_3; i_a is negative, i_b is positive, i_c is positive


a
a'
b
b'
c
c'
N
S
t_1
t_2
t_3
t_4





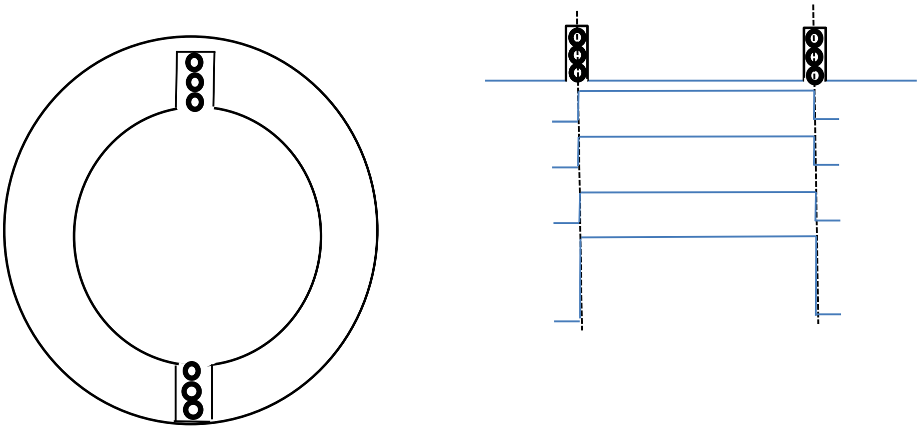




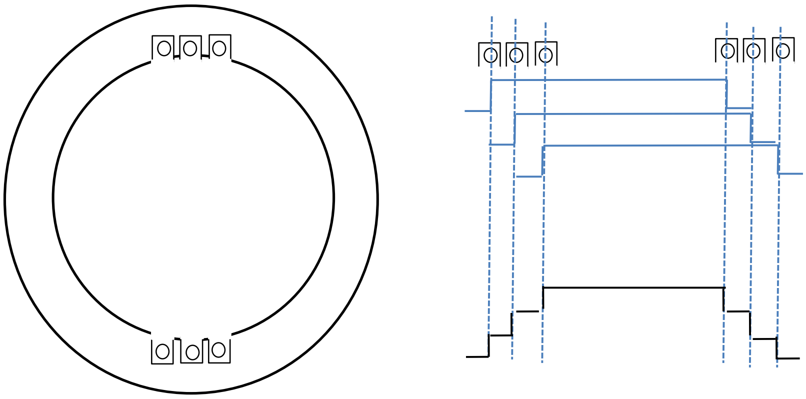
1. If the two consecutive winding section are allowed to carry the currents in opposite direction, then only there will be a pole formation between them
2. If the two consecutive winding section are allowed to carry the currents in same direction , then there will not be any pole formation between them
3. If each phase of induction machine contain “p” number of poles, then the induction machine can be treated as “p” pole machine.
4. Normally in a three phase machine, stator winding are distributed as well as shorted pitched just like synchronous machine in order to reduce copper and harmonics.
5. The nature of poles formed by single phase system are alternating
6. The nature of poles formed by three phase systems are rotating.
7. A pole pair combination can be changed to another pole pair combination by changing the end connection
8. In D.C machine poles are projected inside and are visible. So it is called ***Hetropolar*** construction.
9. In Induction machine poles are distributed over entire surface of stator core and are not visible. This construction is ***Homopolar*** construction machine.
10. No of pole mentioned on name plate of Induction machine represents No. of poles available on each phase of the stator winding

Placing of Stator winding in the stator slots

Concentrated winding



Distributed windings



The Air gap MMF wave for **concentric winding** induction machine is **rectangular** waveform as shown in fig.

The Air gap MMF wave for **distributed** winding induction machine is **trapezoidal** waveform as shown below.

The trapezoidal wave form shape is nearer to sinusoidal wave form and space harmonics are less in trapezoidal wave form compared with rectangular wave form.

For n^{th} harmonic pitch factor is $K_{pn} = \cos\frac{n\alpha}{2}$

For n^{th} harmonic distribution factor is $K_{dn} = \frac{\sin\frac{mn\beta}{2}}{m\sin\frac{n\beta}{2}}$

Rotor

Based on the rotor construction, the induction motor are classified into,

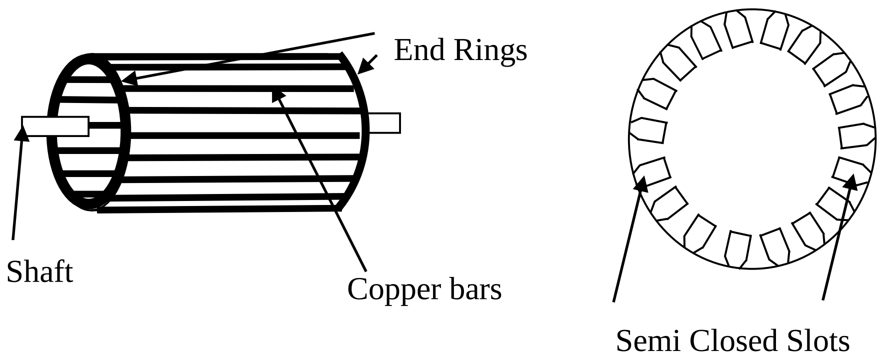
- ❖ Squirrel cage induction motors and
- ❖ Slip ring induction motors.

These motors differs only with respect to rotor construction, the stator construction is same for both the motors

(i) Construction feature of squirrel cage rotor

1. Rotor core is made up silicon steel laminations
2. Rotor laminations are made up of thick lamination as rotor frequency is (1- 4) Hz.

   Note: Eddy current loss in rotor core is very less as frequency of induced current in rotor core is very low, so we can use thick lamination for rotor core, whereas stator core is having thin laminations as the frequency of induced currents in the stator core is always supply frequency



3. On the rotor outer periphery semi open type slots re preferred and in semi open type slots, heavy copper bars are inserted.
4. To facilitate a closed path in the rotor circuit, the either side of the rotor bars are short circuited by end rings. Because of the end rings current pass from one bar to another bar.
5. End rings are made up of forged special copper and end rings has to provide good mechanical support to the rotor bars, not to come out of the slots, so the strength of the end rings should be more

   End Ring properties –

   (i) Good Mechanical strength

   (ii) Good conductivity
6. Forging is a process which is used to increase the hardness/ strength of the material

❖ ***Features of squirrel cage Rotor:***

1. This type of rotor has no definite number of poles, but the same number of stator poles will be induced in the rotor automatically by means of induction.
2. As rotor poles are induced poles, so this type of rotor can respond automatically to the changes in the stator number of poles. *i.e*. when the stator poles are changed, automatically rotor poles are changes accordingly.
3. In squirrel cage rotor there are no definite number of phases, but one can treat this squirrel cage rotor with

Number of phases = Number of copper bars under one pole

4. (a) The operation of induction machine is possible even though stator and rotor number of phases are unequal

(b) The operation of induction machine is not possible with unequal number of stator and rotor poles

5. As this type of rotor has smooth outer surface, thin air gap is enough between the stator and rotor, therefore it reduces the magnetizing component of current required and increases no load and full load power factor of the machine.

6. This squirrel cage rotor does not contain windings and winding over hang, therefore its leakage reactance is low and it results in high maximum torque under running conditions.

Drawbacks

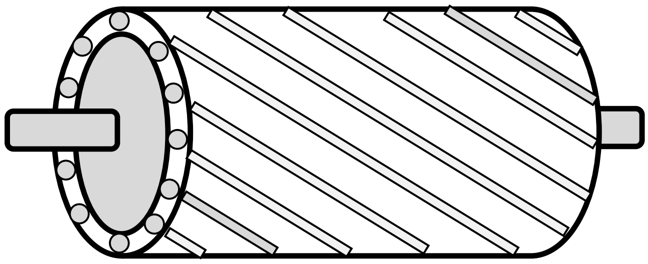
1. ***Low starting torque***: This squirrel cage rotor offer low rotor winding resistance, therefore its starting torque is poor.
2. ***High starting currents***: As this rotor has low rotor winding , and impedance at the time of starting , it draws high starting currents.(So some external starting methods are required to start this type of induction motors)
3. ***Poor Power factor:*** Due to low rotor winding resistance, this rotor has poor starting power factor.

Conclusions: This type of induction machine produces good running performance but poor starting performance.

But however the starting characteristics of squirrel cage induction motor can be partially improved by modifying the rotor circuit design

1. ***Skewed rotor slots/bars***
2. ***Deep Bars***
3. ***Double cage rotors***

(i) Skewed Rotor slots/Bars



Functions of skewed rotor slots in Induction motor

1. The skewed rotor slot increases the length of the copper bar thereby increases the resistance of the rotor bars and hence starting performance of the induction machine
2. It makes the air gap flux distribution uniform there by reduces harmonics torque produced by the machine.
3. As harmonic torque are reduced the following phenomenon's due to harmonic torque can also be reduced
   (a) Cogging / Magnetic Locking at the time of starting conditions
   Cogging tendency can be overcome by making the number of rotor slots prime to the number of stator slots. Cogging tendency can also be reduced by above said skewing the rotor slots
   (b) Crawling under running conditions
   The crawling effect may be eliminated or reduced by properly designing the stator winding, so as to reduce the harmonics in the air gap flux wave. The crawling effect can also be eliminated by proper choice of rotor slots in comparison to stator slots
4. Its reduces noise and vibrations there by helpful to get smooth and silent operation of the machine

COGGING: when the no. of rotor slots is equal to the number of stator slots, the speed of all the harmonics by the stator slotting coincide with the speed of corresponding rotor harmonics. Thus harmonics of every order would try to exert synchronous torques at their synchronous speeds and the machine would refuse to start. This is known as **cogging** or **magnetic locking**. Therefore the no.of stator slots

should never be equal to the rotor slots. Cogging can be easily overcome by making no. of rotor slots prime to no. of rotor slots.

CRAWLING: The tendency of particularly squirrel-cage rotor to run at speeds as low as one-seventh of their synchronous speed. This phenomenon is known as **crawling** of an induction machine

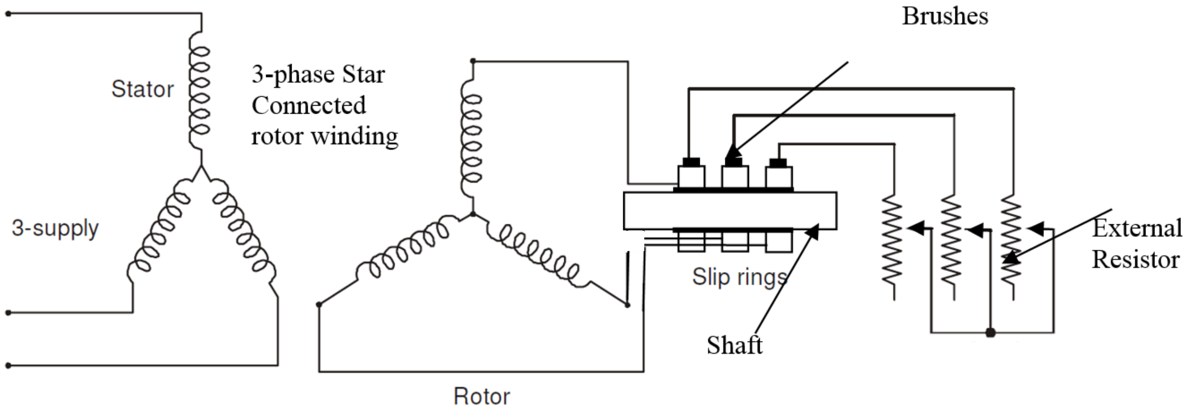
(ii) Slip ring rotor/wound rotor

1. Rotor core is made up of laminated silicon steel
2. The thickness of laminations are more than the stator laminations.
3. Winding are placed in the slots (Semi-closed type slots)

❖ ***Conditions to be satisfied while placing the rotor winding***

1. The rotor winding must be distributed as well as short pitched just like the stator winding
2. As operation of induction machine is not possible with unequal number of stator and rotor poles, while placing the rotor winding while placing poles, Number of Rotor poles must be made equal to Number of stator poles
3. As this type of rotor connect respond automatically to the changes in stator number of poles, whenever the stator number of poles are changed, the rotor number of poles must be changed manually to the same number otherwise there is no motoring
4. Even though stator is wound with three phases the rotor need not be provided with three phases , but it can be provided for any number of phases except single phase(In practice rotor and stator are wound for three phases)
5. In actual practice the rotor is also provided with the same three phases as the stator winding, to get good mechanical balance of the rotor.
6. If the rotor is provided with three phase windings, the rotor winding must be connected in star irrespective of whether the stator winding are connected in star or delta.

❖ ***Schematic diagram of Slip Ring Induction motor.***



- In slip ring motors, it is essential to bring out the rotor terminals as it gives possibility of inserting an additional resistance in the rotor circuit. The three terminals of the star connected rotor windings are brought out and are connected to the external resistors through the slip ring and brush arrangement mounted on shaft..
- Slip ring are placed on the rotating shaft and are insulated from the rotating shaft by mica insulation.
- The shaft of an induction motor is short and stiff, in order to keep as small an air-gap as is mechanically possible and it is made up of MILD steel. This helps in removing any significant deflection in the rotor. Even a small deflection in the shaft, and hence rotor, would create large irregularities in the air-gap length which would lead to production of unbalanced magnetic pull. For small and medium capacity motors, a roller bearing may be used at the driving end and a ball bearing at the non-driving end.
- Brushes sliding on the slip rings are used for making connection of rotor windings with the external circuit. Brush lifting and short-circuiting gear it used for operating the brushes.
- Brushes are made up of carbon material (If we use copper brushes frictional loss is more). Carbon is a material having the property of self-lubrication. So frictional loss with the carbon brushes are less
- Slip-rings are normally of brass or phosphor-bronze shrunk onto a cast-iron sleeve with moulded mica insulation. The assembly is pressed onto the rotor shaft and located either between the rotor core and the bearing, or onto the shaft extension. This part is exclusively in slip-ring motors and not in the common type squirrel cage motors.
- To improve the starting torque external resistors are used. The brushes are continuously touching the slip ring.

❖ ***Functions of star connected external rheostats in slip ring Induction motor***

1. The external resistance increases the staring torque produced by the Induction motor
2. This external resistance also limits the starting current drawn by the motor at the time of starting, hence no external starting method is required to start this type of induction motor.
3. Starting power factor of the rotor improves at the time of starting

4. If the external resistance is inserted under running conditions by varying the external resistance the speed of the induction is controlled. This control is called rotor rheostatic control method

COMPARISON OF SQUIRREL CAGE AND SLIP RING INDUCTION MOTOR

Squirrel cage Induction Motor (Advantages)	***Slip ring Induction Motor (Advantages)***
1. Rugged in construction	1. Much higher starting torque(by inserting resistances in rotor circuit)
2. No Slip rings, brush gears etc	2. Comparatively lesser starting current (2 to times full load current)
3. Minimum maintenance	3.Capable of starting with load demanding high starting torque
4. Cheaper	4. Speed control(by varying resistance in the rotor circuit)
5. Trouble free performance	5. Can be started directly on lines (resistance in the rotor circuit acts like a starter and reduces the starting current)
6. Comparatively higher efficiency	
7. Possible to obtain medium starting torque by double cage rotor or by deep rotor	
8. Relatively better cooling conditions	
9. Comparatively better pull out torque and over load capacity	
Squirrel cage Induction Motor (Disadvantages)	***Slip ring Induction Motor (Disadvantages)***
1. Low Starting torque	1. High cost
2. Higher starting current(5 to 6 times the full load current)	2. Comparatively lower efficiency
3. No speed control	3. Higher degree of maintenance
4. Needs a starter	4.Extra losses in external resistance , especially when operated at reduced speed.
5. Cannot be used for loads demanding high starting torque	5.Extra slip rings, brush gears etc

Conclusions:

Due to provision of extra resistance in case of slip ring induction motor, this type of induction motor has good starting performance but inferior running performance such as more magnetizing current component of current, No load and full load power factor are less. Less maximum torque under running condition when compared to squirrel cage induction motor

The squirrel cage induction motor has good heat dissipation capability ,the over loading capacity of squirrel cage induction motor is more when compared to slip ring induction motor

Squirrel cage Induction motor $\cos\phi_{fl} = 0.85\ lag$

Slip ring Induction motor $\cos\phi_{fl} = 0.8\ lag$

1. A 3-phase, 4 pole squirrel cage induction motor has 36 stator and 28 rotor slots. The number of phases in the rotor is (GATE 2000)			
(a)	3	(b)	9
(c)	***7***	(d)	8
2.The rotor slots are slightly skewed in squirrel-cage induction motor to (IES-2001)			
(a)	increase the strengths of rotor bars	(b)	***reduce the magnetic hum and locking tendency of rotor***
(c)	Economies on the copper to be used	(d)	Provide ease of fabrication
3.Skewing of the rotor in a three-phase squirrel-cage induction motor reduces (IES-2001)			
(a)	***noise, parasitic torque, starting torque and pullout torque***	(b)	noise and parasitic torque, but increases starting torque and pullout torque
(c)	noise and pullout torque, but increases parasitic torque and starting torque	(d)	noise, parasitic torque and starting torque, but increases pullout torque
4. The rotor of a three phase, 5 kW, 400 V, 50 Hz, slip ring induction motor is wound for 6 poles while its stator is wound for 4 poles. The approximate average no load steady state speed when this motor is connected to 400 V, 50 Hz supply is			
(a)	1500 rpm	(b)	500 rpm
(c)	***0 rpm***	(d)	1000 rpm

- **Length of Air Gap:**

Performance like power factor, magnetising current, over load capacity, cooling, noise are affected by the length of the air gap. Following are the major advantages and disadvantages of providing a larger air gap in induction motor.

Advantages

1. ***Increased over load capacity*** –zig zag flux is reduced, resulting in decreased values of zig-zag leakages reactance, which forms a major part of the total leakage reactance .The diameter of the circle diagram for 3-phase induction motor increases with decreased value of leakage reactance. The over load capacity of the motor increases with increased diameter of the circle diagram

2. ***Reduction in noise***- Zig zag flux is reduced, which causes a reduction in noise in induction motor

3. ***Improved Cooling***- Because of increase distance between the cylindrical surfaces of stator and rotor.

4. Reduction in the ***unbalanced magnetic pull.*** If the length of air gap is small, even a small deflection or eccentricity of the shaft would produce a large irregularity in the length of air gap and is responsible for production of large unbalanced magnetic pull which has the tendency to bend the shaft still more at a place where it is already bent resulting in fouling of rotor with stator. If the length of air gap of a machine is large, a small eccentricity would not be able to produce noticeable unbalanced magnetic pull

5. ***Reduction in tooth pulsation losses***, which are mainly produced due to variation in the reluctance of gap

6. ***Pulsation losses:*** With larger length of air gap, the variation of reluctance due to slotting is small. The tooth pulsation loss, which is produced due to variation in reluctance of the air gap, is reduced accordingly.

Disadvantages:

1. ***Increased magnetisation current***- Total ampere turns required to overcome the reluctance of air gap is directly proportional to length of air gap. If the motor is designed for a larger air gap, magnetising current drawn by the motor would be a larger percentage of the full load current.

2. ***Reduced power factor***: Phasor diagram of 3-phase induction motor drawn for two different values of magnetising current (Fig –a and Fig –b) clearly indicates, that the operating power factor is lesser for the motor which draws higher magnetising currents. Hence power factor is reduced ,when the motor is designed for larger air gaps

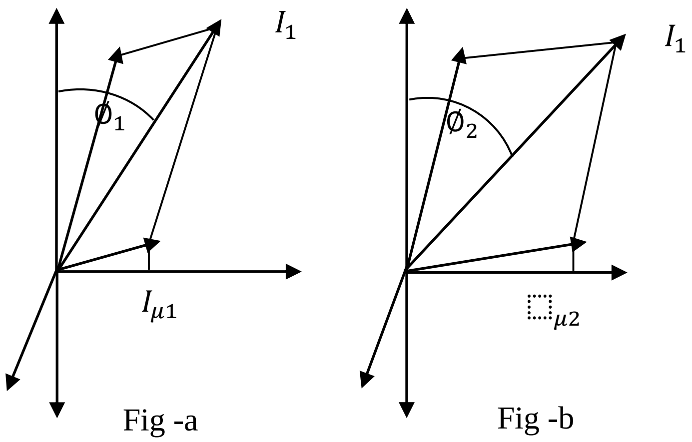


Fig -a Fig -b

Magnetising current and the power factors being extremely important performance parameters, the induction motor should be designed for a small air gap as mechanically possible

During the design calculations, the length of the air gap can be calculated by the following empirical formula, which aims at reducing the magnetising current and improvement in power factor

(i) Air gap length, $l_g=0.2+\sqrt{LD}$ mm

Where internal diameter of stator, D and gross length, L in meters

(ii) Another formula which can be used for small machines , is

$$l_g=0.125+0.35D+L+0.015V_a \text{ mm}$$

Where V_a is the peripheral speed in meter per second

(iii) The following relation may be usefully used

$$l_g=0.2+D \text{ mm}$$

The following air gaps may be used for 4 pole machine;

D(m)	lg(mm)	D(m)	lg(mm)
0.15	0.35	0.45	1.3
0.20	0.50	0.55	1.8
0.25	0.60	0.65	2.5
0.30	0.70	0.80	4.0

Rotor diameter D_r = Stator Internal diameter (bore) − 2× length air gap = $D-2l_g$

1. Which one of the following statements is correct? A smaller air gap in a polyphase induction motor helps to(IES-2004)

(a) reduce the chances of crawling
(b) increase the starting torque
(c) reduce the chance of cogging
(d) ***reduce the magnetizing current***

2. Which one of the following statements is correct? In an induction motor, if the air gap is increased, (IES-2004)

(a) its speed will reduce
(b) its efficiency will improve
(c) ***its power factor will reduce***
(d) its breakdown torque will reduce

3. Which of the following parameters in an induction motor influences the magnetizing reactance to the maximum extent(IES-2006)

(a) Axial length of the rotor stack
(b) Axial length of the stator stack
(c) ***Radial length of air gap***
(d) Number of slots on the stator

4 If two induction motors A and B are identical except that the air-gap of motor 'A' is 50% greater than that of motor 'B' then (IES-1997)

(a) The no-load power factor of A will be better than that of B
(b) The no-load power factor of A will be poorer than that of B
(c) The core losses of A will be more than those of B
(d) The operating flux of A will be smaller than that of B

❖ Choice of Air Gap Flux Density

The average air gap flux density must be chosen that there is no saturation in any part of the magnetic circuit. The value of operating flux density in the teeth and core increases with increased value of air gap flux density. Normally flux density in the teeth should not exceed 1.8 Tesla and the flux density in the core should be between 1.3 to 1.5 Tesla. Hysteresis and eddy current losses occurring in teeth and core are the function of flux density in the teeth and

core respectively. Thus, the choice of air gap flux density is extremely important as it effect iron losses, over load capacity, power factor, cost, size an temperature rise.

Advantages of higher flux density

1. Size of the machine is reduced for the same output
2. Cost of the machine decreases
3. Over load capacity increase

Disadvantage

1. Higher no load current, because of large magnetising current and increased iron loss component
2. Poorer power factor, because of large magnetising current
3. Increases iron losses, because of higher flux density in the stator teeth and core
4. Higher temperature rise
5. Increased noise

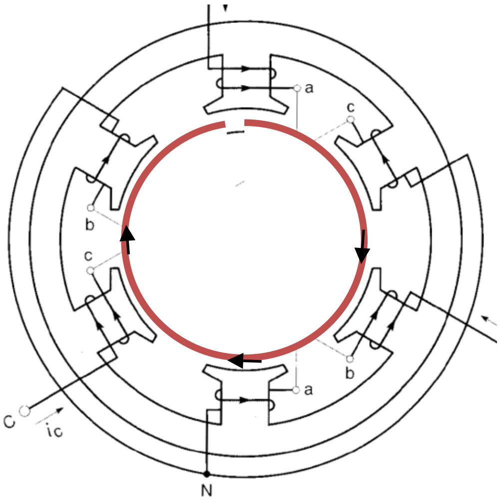
Note:

1. Average value of flux density in the air gap can be assumed varying from 0.35 to 0.6 Tesla, the lower value for smaller machines
2. Comparatively ,higher value of gap flux density can be assumed for (i) low voltage machines (ii) machines with small number of poles (iii) machines of larger output

Case 1: If the excitation is given to the stator winding with rotor winding short circuited (General Case)

Consider an induction motor with both its stator and rotor windings connected in star. The rotor winding is assumed open circuited at starting so that rotor current is zero and no electromagnetic torque is developed.

When a balanced three phase excitation at line frequency "f" is given to the star connected stator winding, a constant magnitude rotating magnetic field (called Stator Rotating Magnetic field (SRMF)) is produced in the air gap, which rotates with a speed N_s with respect to the stator structure.



As there is a relative speed between the stationary stator conductors and the SRMF, an emf is induced in the stator winding according to Faradays law, and it is given as

$E_1/ph=4.44f_1\Phi_1N_1Kw_1$,

where f_1 is the frequency of induced emf in the stator winding , N_1 stator turns /ph and Kw_1 is the winding factor , as the stator winding are distributed and short pitched.

$f_1=\frac{(Relative\ speed)\times P}{120}=\frac{N_SP}{120}$ =f (supply frequency)

$E_1/ph=4.44f\Phi_1N_1Kw_1$

Observation 1: The speed of the stator rotating magnetic field (SRMF)/stator field with respect to stator structure is N_s (synchronous speed).

Observation 2: The frequency of induced emf in the stator winding is always equal to supply frequency (f_1=f)

At the same time, as there is a relative speed between the stationary rotor conductors and SRMF, hence emf is induced in the rotor winding also according to Faradays law and is given as

E_{20}/ph=4.44$f_2\Phi_1N_2Kw_2$,
where f_2 is the frequency of induced emf in the rotor winding , N_2 rotor turns /ph and Kw_2 is the winding factor , as the rotor winding are also distributed and short pitched.

$f_2=\frac{(Relative\ speed)\times P}{120} = \frac{N_SP}{120}$ =f (supply frequency)

E_{20}/ph=4.44 f Φ_1 N_2 Kw_2

Observation 3: The frequency of induced emf in the rotor winding at starting(standstill conditions) is equal to supply frequency (f_2=f)

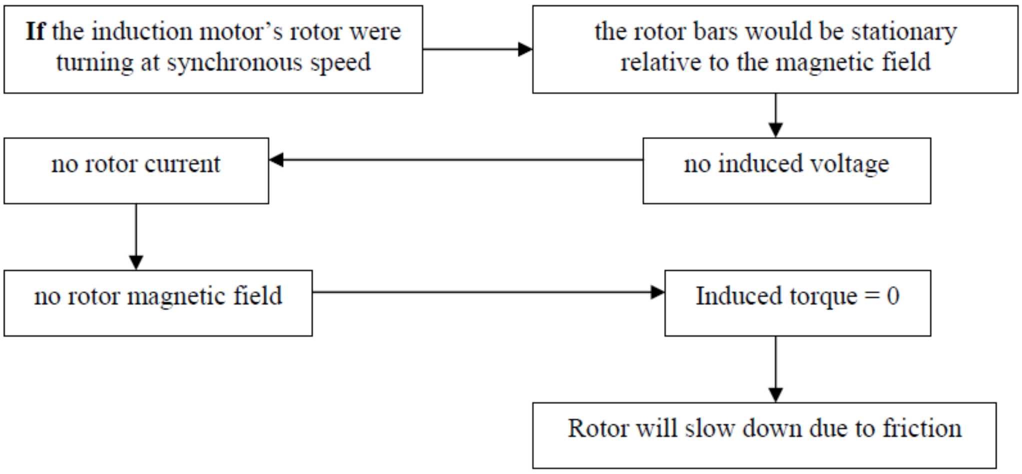
The rotor circuit is short circuited (closed), so that the induced emf in the rotor circuit give rise to the rotor current.

$$I_{2/ph} = \frac{E_2}{Z_2}$$

The interaction of these rotor currents with rotating magnetic field (flux) experiences a force and produces torque in the rotor of a 3-phase induction motor (according to Lorentz force equation) and as a consequence, rotor begins to rotate.

According to Lenz's law, effect opposes the cause. Here, effect is the developed torque and cause is the flux-cutting by the rotor conductors. Therefore, as per Lenz's law, the developed torque must oppose (or minimize) the cause, that is flux -cutting action. This is possible only if the developed torque forces the rotor to rotate in the direction of the rotating field .When this happen , the relative speed between the rotating flux and rotor conductor is reduced and therefore the flux cutting action also get reduced. As such the rotor rotates in the same direction as that of the rotating magnetic field so as to obey Lenz's law, thus the motor is self-starting and the rotor acquires a steady state speed of N_r (which is always less than N_s) depending upon the shaft load

Observation 4: If the rotor is assumed to run at synchronous speed N_s in the direction of rotating magnetic fields, then there would be no flux cutting action, no emf in the rotor conductors, no currents in the rotor bars and therefore no developed torque. Thus, the rotor of 3-phase induction motor can never attain synchronous speed



Observation 5: The speed of the rotor structure with respect to stator structure is N_r

With the rotor running at N_r, the relative speed of the stator rotating magnetic field with respect to the rotor conductors is N_s-N_r in the direction of Ns and this relative speed is referred as slip speed. The frequency of induced emf's (and currents) in the rotor is therefore.

$$\text{slip speed} = N_s - N_r \,;$$

$$\text{Per unit slip or slip (s): } \frac{N_s - N_r}{N_r}$$

$$\text{and the rotor speed } N_r = N_s\,(1-s)$$

$$f_2 = \frac{(Ns-Nr)P}{120} = \frac{(Ns-Nr)PNs}{Ns\,120} = \left(\frac{Ns-Nr}{Ns}\right)\frac{PNs}{120} = sf$$

$$E_2/ph = 4.44 f_2 \Phi_1 N_2 Kw_2 \text{ and } f_2 = sf \,;\; E_2/ph = 4.44 f_2 \Phi_1 N_2 Kw_2$$

$$E_2/ph = 4.44 sf \Phi_1 N_2 Kw_2 \,;\;\; E_2 = s\, E_{20}$$

Observation 6: If the rotor is made to revolve in a direction opposite to the rotating magnetic field, then the relative speed between the rotor winding and the rotating magnetic flux becomes N_s+N_r ,and slip become

$s_b = \frac{N_s+N_r}{N_s} = \frac{N_s+N_r+N_s-N_s}{N_s} = 2-s$ and the emf induced per phase of the rotor winding is given by

$$\mathbf{E_2/ph = 4.44\,(2-s)\,f\,\Phi_1\,N_2\,Kw_2}$$

$$\mathbf{E_2 = (2-s)\,E_{20}}$$

Now as the rotor also carries a three phase windings displaced by 120 degrees and three phase induced currents, which have a time angle of 120, there is one more rotating magnetic field, in the air gap produced by these rotor currents (called rotor rotating magnetic field (RRMF)), which rotates with a speed sN_s with respect to rotor structure as the induced emf frequency in the rotor conductors during running is sf.

The speed of the rotor field with respect to stator is equal to the sum of mechanical rotor speed Nr, and the rotor-field speed sN_s, with respect to the rotor. Thus the speed of rotor field with respect to stator is given by

$$N_r+sN_s=N_s \text{ rpm}$$

But the stator field speed with respect to the stator is synchronous speed N_s rpm. This concludes that the stator and rotor field are stationary with respect to each other at all possible rotor speeds. Since the relative speed between the stator and rotor field is zero, a steady torque s produced by their interaction and rotation is maintained.

Observation 7: The speed of the rotor field with respect to stator structure is sum of speed of the rotor with respect to stator and speed of the rotor field with respect to rotor $Nr+sN_s= N_s$

Observation 8: The speed of the rotor field at starting with respect to rotor (stator) is N_s

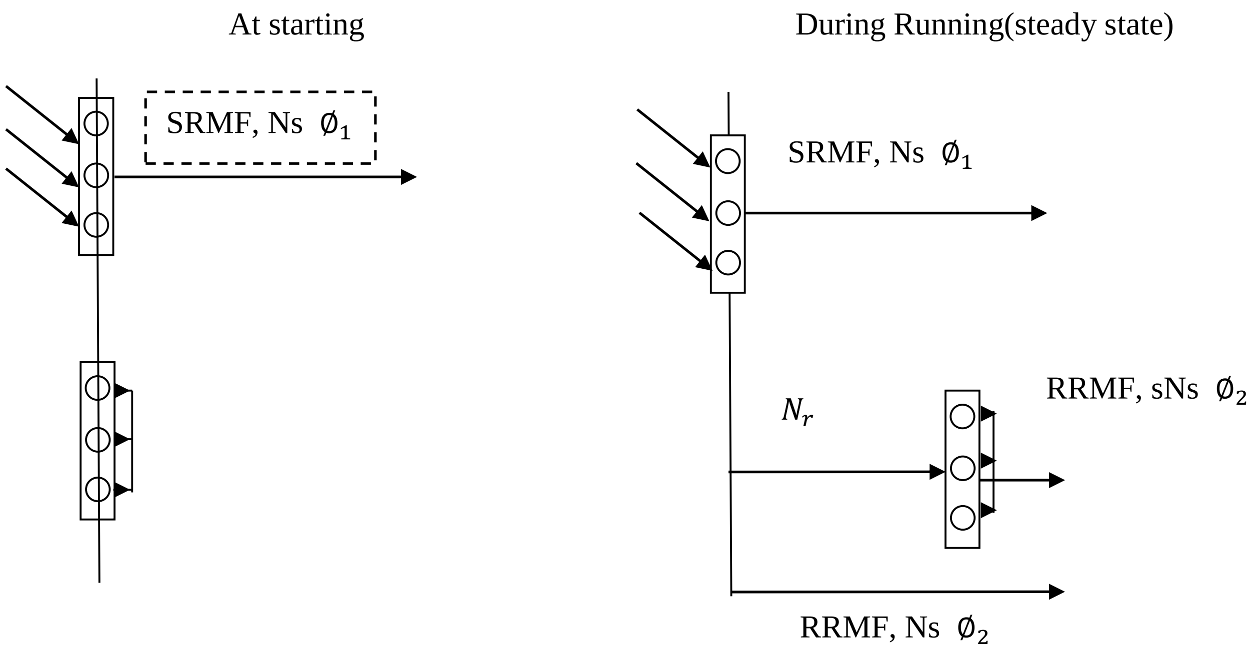
Observation 9: The speed of the rotor field with respect to stator field is ZERO, which are stationary with respect to each other.

$$\emptyset_r = \emptyset_1+\emptyset_2$$

$$E_1/ph=4.44f_1\Phi_rN_1Kw_1$$

$$E_2/ph=4.44f_2\Phi_rN_2Kw_2$$

Line Diagram



1. ***A 3-phase induction motor runs at a speed of 1485 rpm at no-load and at 1350 rpm at full load when supplied from a 50 Hz, 3 –phase line.***

(a) How many poles does the motor have? Ans:4

(b) What is the % slip at no-load and at full load? Ans:0.01; 0.1

(c) What is the frequency of rotor voltages at no-load and at full load? Ans: 0.5Hz;5Hz

(d) What is the speed at both no-load and full load ; (i) the rotor field with respect to the rotor conductors, (ii) the rotor field with respect to the stator , and (iii) the rotor field with respect to the stator field Ans:15rpm; 150 rpm;1500rpm;0rpm

2. ***A slip ring – induction motor runs at 285 rpm on full when connected to 50-Hz supply. Calculate the (a) the number of poles; (b) the slip; and (c) the slip for full-load torque if the total resistance of the rotor circuit is doubled. Assume the rotor leakage reactance to be negligible in the range of slip being considered.***

   Ans: 20poles: 0.05; 0.1

3. ***The stator of a 3-phase, 4 pole slip ring induction motor is connected to 50 Hz supply. At the rotor terminals, a frequency of 30 Hz is required. Find the possible speeds at which the rotor must be driven.***

   No of poles (P) : 4

   Supply frequency(f) : 50 Hz

   Synchronous Speed : $N_s = \frac{120f}{P}$ = 1500 rpm

   Rotor frequency f_2=30 Hz; we have $s = \frac{f_2}{f} = \frac{30}{50} = 0.6$;

   Rotor speeds are; $N_r=N_s(1-0.6)$= 600 rpm or $N_r=N_s(1+0.6)$=2400 rpm.

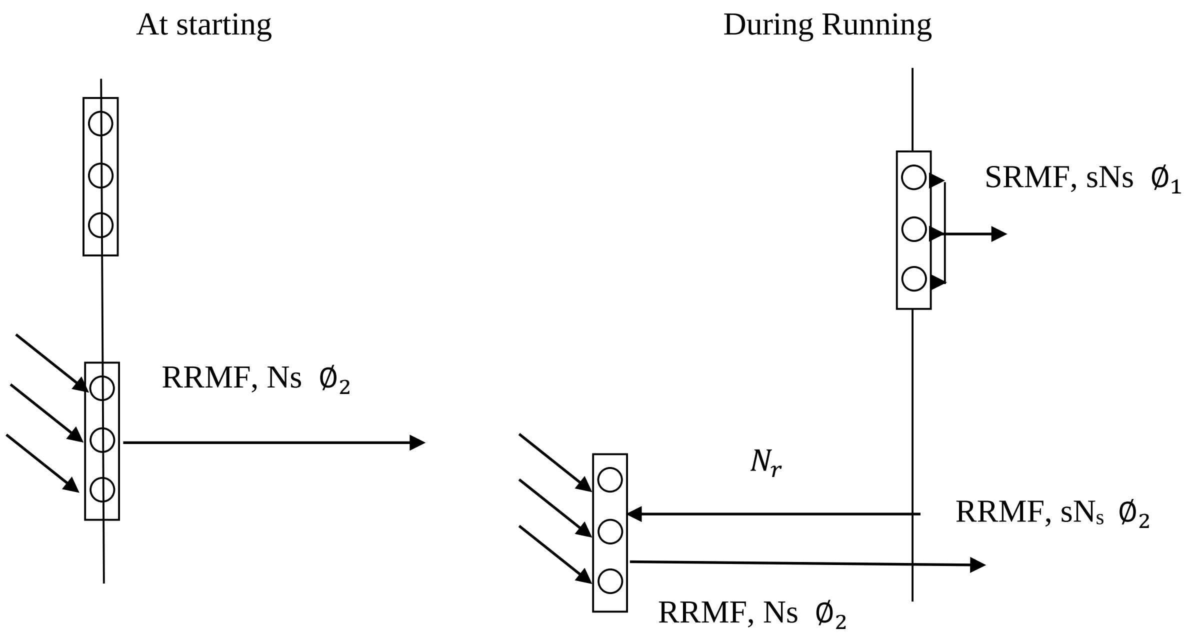
4. ***A 6-pole, 50 Hz wound-rotor induction motor when supplied at the rated voltage and frequency with slip rings open circuited, develops a voltage of 100 V between any two rings. Under the same conditions its rotor is now driven by external means at***

(a) 1000 rpm opposite to the direction of rotation of stator field, and

(b) 1500 rpm in the direction of rotation of stator field.

Find the voltage available between the slip-rings and its frequency in each of these cases.

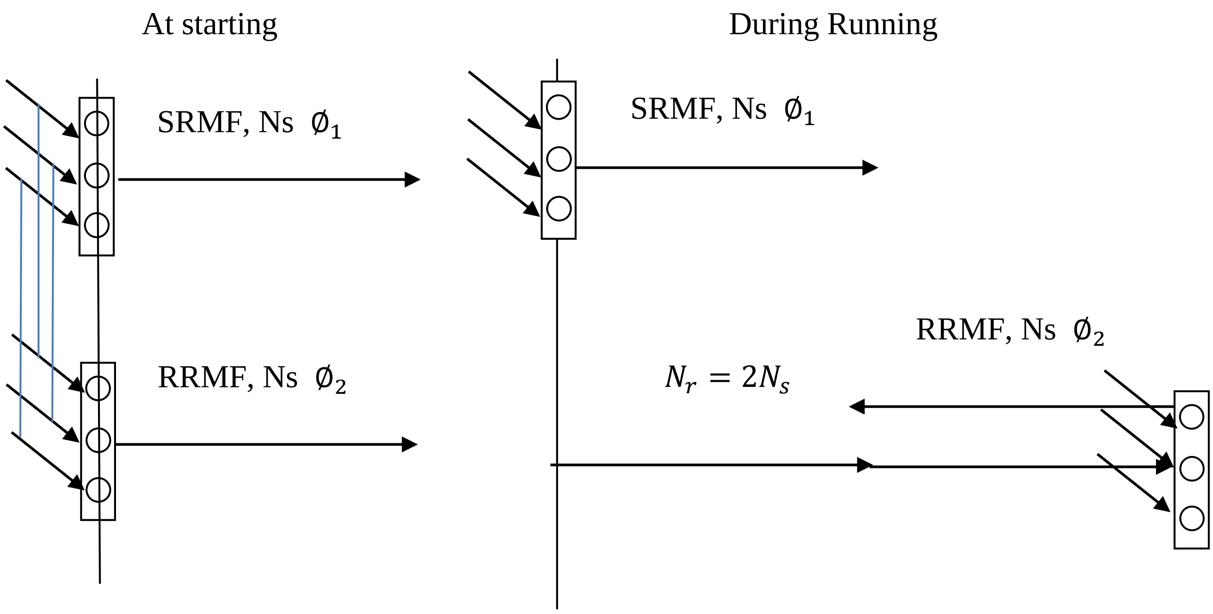
Case 2 If the excitation is given to the rotor winding with the stator winding short circuited



If the excitation is given to the rotor terminals with line frequency with stator terminals short circuited, the rotor rotates in a direction opposite to the rotating magnetic field produced by the rotor current, with a speed N_r, which is less than N_s, to obey Lenz's law.

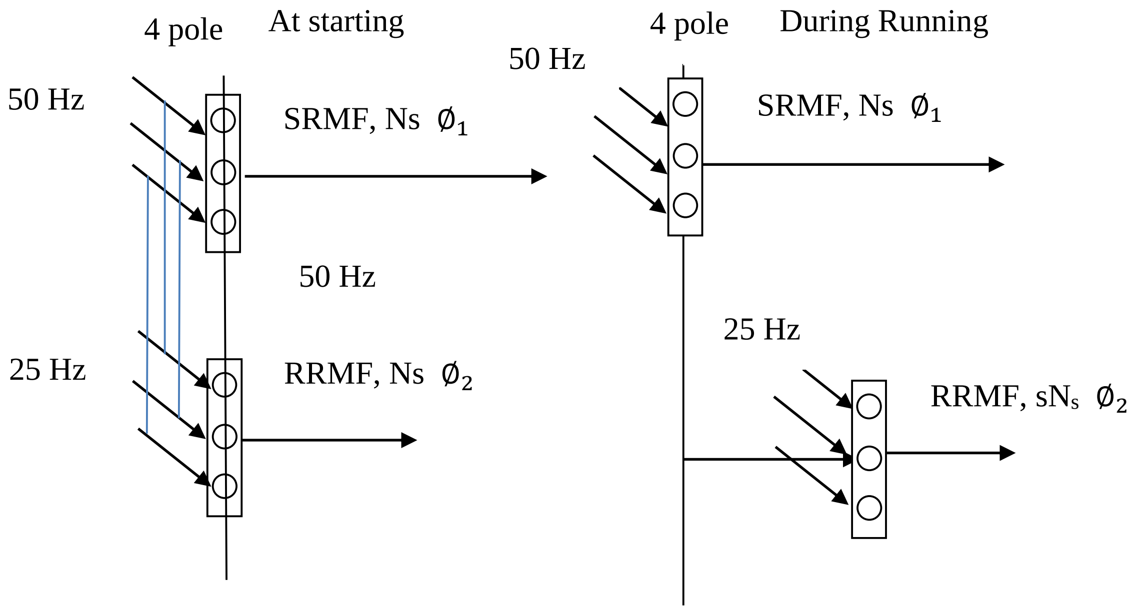
Case 3 If the excitation is given to the stator rotor winding

(a) With same Frequency :



(i) ***If the rotor field rotates in the same direction as the stator field, steady state (synchronous) operation is only possible at zero speed. At any other speed of the two fields will have relative motion and will produce a zero torque.***

(ii) ***If the rotor field rotates opposite to the stator field, the steady (synchronous) operation will results when the rotor moves at 2 Ns rpm in the direction of the stator fields ; it is only at this speed of the rotor that the two fields are relatively stationary***



(i) ***If the rotor field rotates in the same direction as the stator field, steady state (synchronous) operation is only possible at 750 speed. At any other speed of the two fields will have relative motion and will produce a zero torque.***

5. ***The stator of the induction motor in the above problem is fed at the rated voltage and frequency while its slip-rings are connected to a 25 Hz supply.***
   (a) Will there be a starting torque?
   (b) At what speed will steady operation results?
   (c) At what speed will steady operation result if the rotor is also fed with 50 Hz supply

6.A 4-pole synchronous generator driven at 1500 rpm feeds a 6 pole induction motor which is loaded to run at a slip of 5% what is the motor speed.

Frequency of synchronous generator (Excitation frequency to motor)

$$f = \frac{4 \times 1500}{120} = 50\text{Hz}$$

Synchronous speed of Induction motor

$$N_s = \frac{120 \times 50}{60} = 1000 \text{ rpm}$$

Motor slip s = 0.05

Motor speed = $N_s(1-s)$

$= 1000 \times 0.95 = 950$ *rpm*

7. A 3-phase 4 pole 50 Hz, slip ring induction motor has 420 stator turns and 240 rotor turns. The magnitude of the rotating flux per pole is 30 mwebers. The winding factor for both stator and rotor windings are 0.96. Calculate the frequency and the magnitude of per phase emf's in the stator and rotor windings when the rotor is

(a) Stationary

(b) Revolving in the direction of rotating flux wave at a speed of 1440 rpm and

(c) Revolving opposite to the direction of rotating flux wave at a speed of 1440 rpm

(a) When the rotor is stationary

$E_1/_{ph}=4.44 f_1 \Phi_r N_1 Kw_1$

Given $f_1=f = 50$ Hz; $\Phi_r=30$ mwb; $N_1=420$; Number turns / ph = 420/3=140; $K_{w1}=0.96$

$E_1/_{ph}= 895.10$ Volts

$E_2/ph=4.44 f_2 \Phi_r N_2 Kw_2$

At starting $f_2=f =50$ Hz;

$N_2= 240/3=80$, No of rotor turns/ph

Therefore $E_{20}/ph=511.48$ Volts

(b) There is no change in the stator voltage and frequency

But the rotor voltage and frequency changes

$f_2= s f$;

$$s = \frac{N_s - N_r}{N_s} = \frac{1500 - 1440}{1500} = 0.04$$

$f_2=0.04 \times 50 =2$ Hz

$E_2/ph= s \times E_{20}=0.04 \times 511.48 =20.45$ V

(c) $s = \frac{N_s - N_r}{N_s} = \frac{1500+ 1440}{1500} = 1.96$

$f_2=1.96 \times 50 =98$ Hz;

$E_2/ph= s \times E_{20}=1.96 \times 511.48 =1002.50$ Volts

❖ *Concept of Slip:*

In practice, the rotor never succeeds in 'catching up' with stator field. If it really did so, then there would be no relative speed between the two (rotor conductors and the stator field), no rotor emf, no rotor current and so no torque to maintain rotation. That is why the rotor runs at a speed which is always less than the speed of the stator field. The difference in speeds depends upon the load on the motor.

The difference between the synchronous speed N_s and the actual rotor speed N_r is known a slip. Though it may be expressed in so many revolutions/second, yet it is usual to express it as a percentage of the synchronous speed. Actually, the term slip is descriptive of the way in which the rotor is "slips back' from synchronism.

$$\% \text{ slip } s=\frac{N_s-N_r}{N_s} \times 100.$$

Sometimes, Ns- Nr is also called as slip speed.

From this the motor speed (rotor speed) can be obtained as

$$N_r= N_s (1-s)$$

8. ***A 60- Hz induction motor has 2 poles and runs at 3510 rpm. Calculate (a) the synchronous speed and (b) the percent slip***

(a) $N_s = \frac{120f}{p}=\frac{120 \times 60}{2} = 3600$

(b) $s = \frac{N_s-N_r}{N_s} = \frac{3600-3510}{3600} = 0.025 = 2.5\%$

9. ***A 3-phase induction motor is wound for 4 poles and is supplied from a 50 - Hz system. Calculate (i) the synchronous speed (ii) the rotor speed, when slip is 4% and (iii) rotor frequency when rotor runs at 600 rpm.***

(a) $N_s = \frac{120f}{p}=\frac{120 \times 50}{4} = 1500\ rpm$

(b) $N_r= N_s(1-s) = 1500\ (1-0.04) = 1440\ rpm$

(c) $f_2 = s\ f = \frac{N_s-N_r}{N_s} \times f = \frac{1500-600}{600} \times 50 = 30\ Hz$

10. ***A properly shunted centre zero galvanometer is connected in the rotor circuit of a 6-pole , 50 Hz wound rotor induction motor. If the galvanometer makes 90 complete oscillation in one minute, calculate the rotor speed***

Solution: One complete oscillation of galvanometer corresponds to one cycle of rotor frequency

Therefore Rotor frequency, f_2= s f= $\frac{No.of\ oscillations\ /minute}{60} = \frac{90}{60} = 1.5$ Hz

Slip, s =$\frac{f_2}{f} = \frac{1.5}{50} = 0.03$

Rotor speed $N_r = N_s(1-s) = \frac{120 \times 50}{6}(1-0.03) = 970\ rpm$

11. The stator of a 3-ph induction motor has 3 slots per pole per phase. If supply frequency is 50 Hz, calculate

(i) Number of stator poles produced and total number of slots on the motor

(ii) Speed of the rotating stator flux (or magnetic field)

Solution:

(i) P = 2n=2 x 3= 6 poles

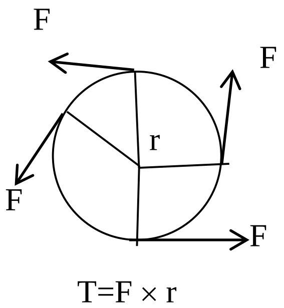
Total Number of slots =3 slots/pole/phase x 6 pole x 3 phase =54

(ii) Ns=1000 rpm

❖ Torque production in AC rotating machine

To rotate the rotor driving force is required. This force is known as torque-turning effect

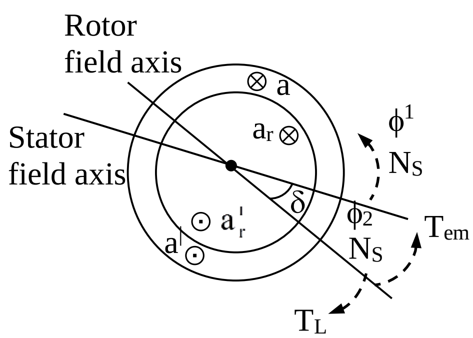
Conditions to produce Torque:



1. Machine has to produce at least two rotating magnetic fields and the relative speed between then is zero.
2. Even though relative speed between them is zero, the two rotating magnetic fields should have relative space displacement between them.

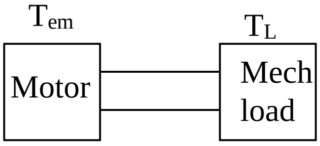
- The torque is produced by interaction between two rotating magnetic fields.
- Rotor is automatically excited by means of Induction.
- Rotor field axis is a variable axis i.e changes, because rotor is movable.

- The two rotating magnetic fields (ϕ_1 & ϕ_2) rotates with speed N_S and have a space displacement between them is δ.
  Where δ = load angle (torque angle)



- Now rotor induced current by Lenz's law is opposes the relative displacement between the (load angle 'δ') rotor and stator axes.

- Rotor field axis is trying to align with stator field axis with the help of electromagnetic torque T_{em}.
- Because of mechanical load torque (T_L) on shaft, the rotor axis is move away from the stator axis.



In motoring mode:

Operation of the machine will be stable only when $T_{em} = T_L$

If mechanical load increases then load torque T_L will increase.

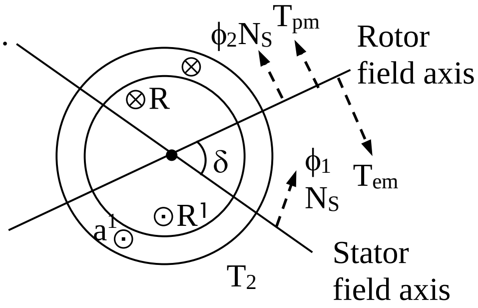
In order to get steady state operation of machine T_{em} has to increase up to $T_{em} = T_L$

In generating mode:

Rotor field axis is in advanced to stator field axis.

$T_{pm} \rightarrow$ torque supplied by prime mover

$T_{em} \rightarrow$ Elector magnetic torque.

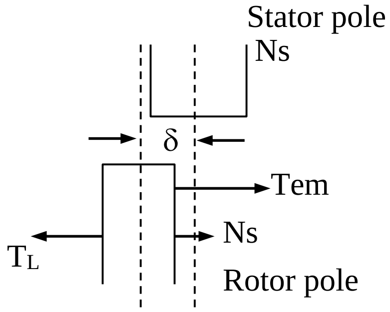


Electromagnetic torque tries to catch the stator field axis and the machine operation is possible only when $T_{pm} = T_{em}$

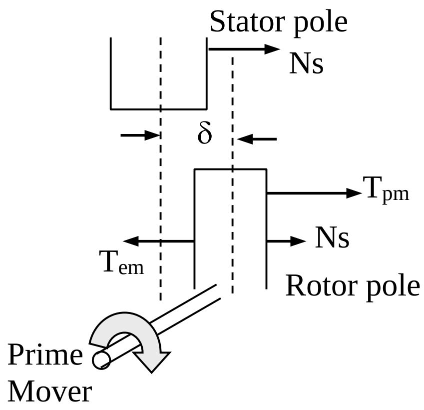
- Direction of T_{em} is same as direction of rotor axis in motor operation, but direction of T_{em} is opposite to the direction of rotor axis in generator operation.
- The electrical energy required by the machine is to produce electromagnetic torque (T_{em}) to overcome the load torque (T_L) in motoring mode.
- The mechanical energy required by the prime mover is to produce prime mover torque to overcome the electromagnetic torque in generating mode.
- If prime mover fails, prime mover torque T_{pm} will decreases gradually and at some point rotor axis is align with stator axis because of windage and friction and finally lagging with stator axis , then it runs as motor under No-load condition.

In synchronous machine:

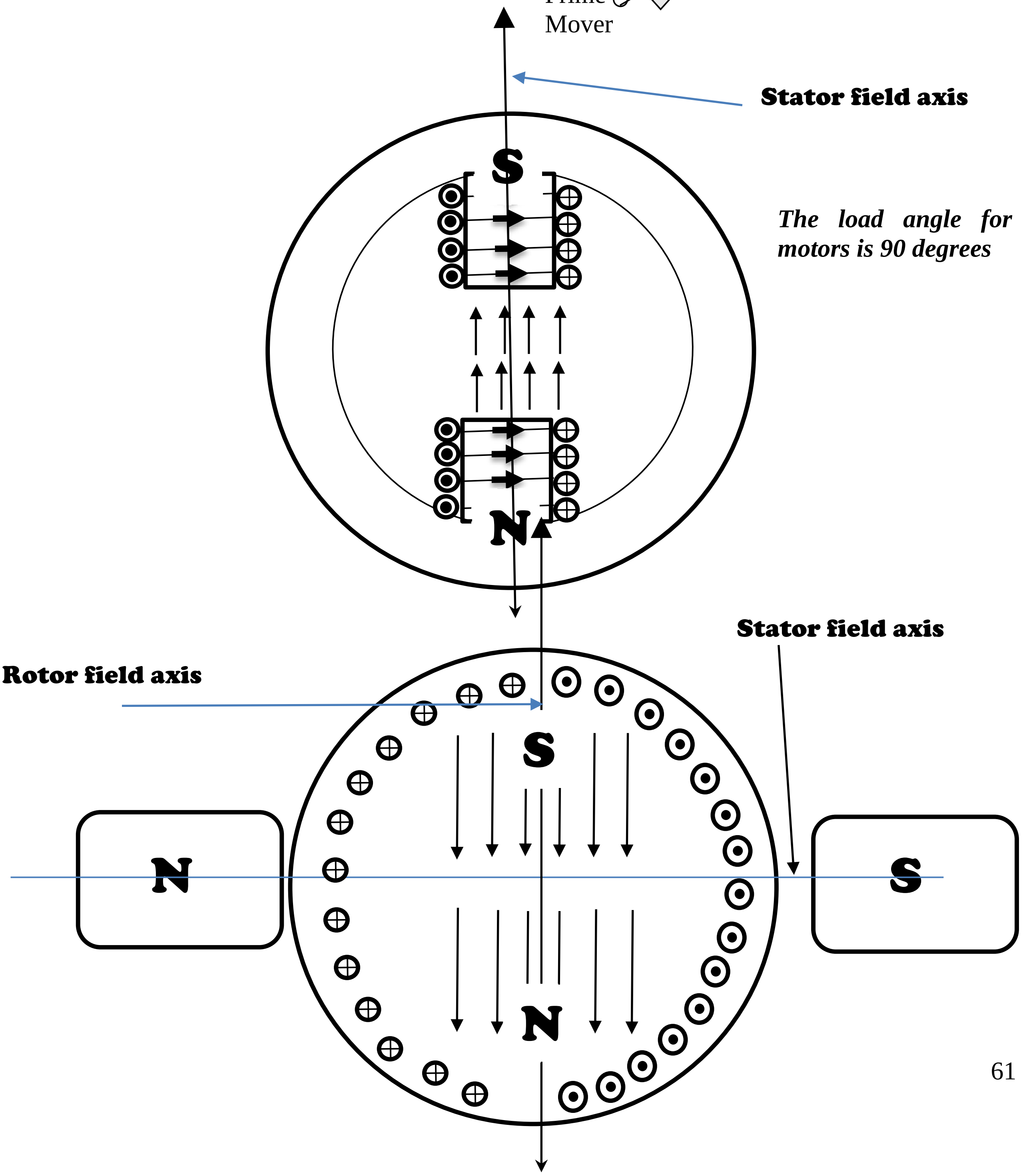
- Motoring mode: (under running condition)
  Electromagnetic torque (T_{em}) tries to align the rotor axis with stator axis.
  $T_{em} = T_L$ at steady state



- Generating mode: (under running condition)
  Electromagnetic torque (T_{em}) tries to catch the stator axis
  $T_{em} = T_{pm}$ at steady state

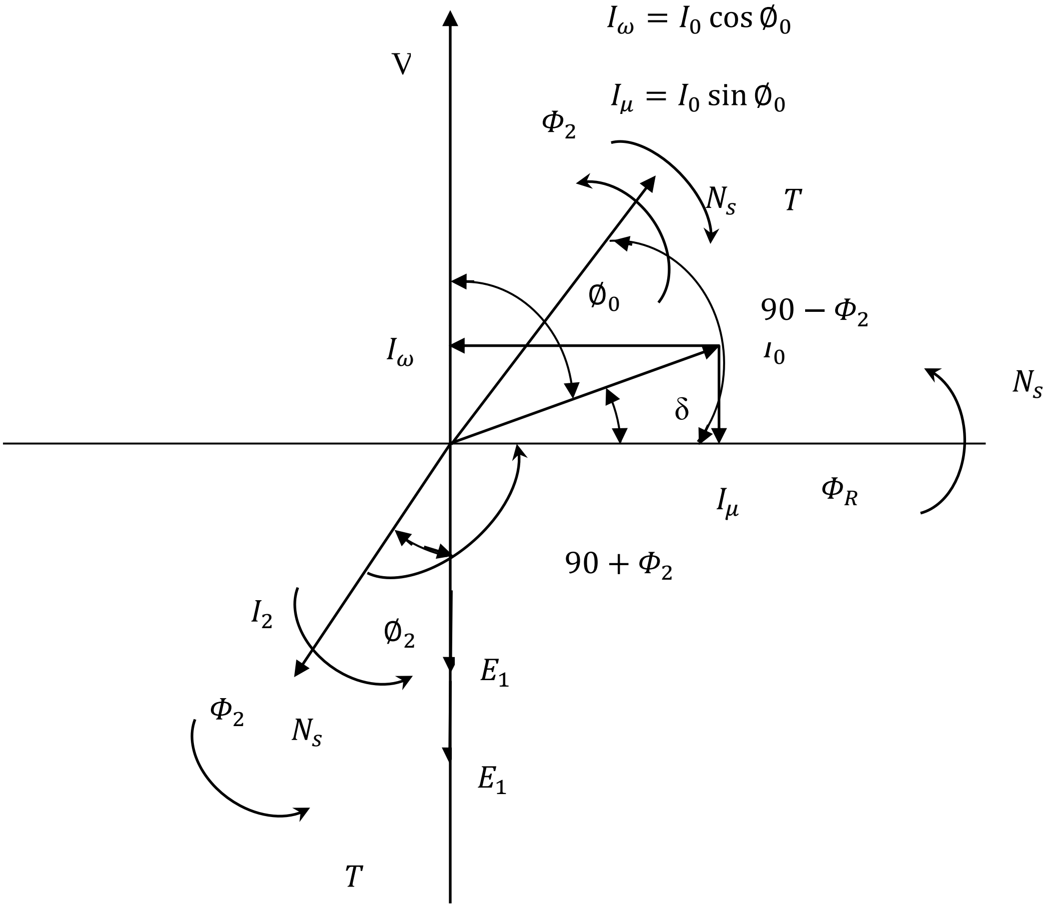


(i) For DC Motors



The load angle for dc motors is 90 degrees

Induction Machines:



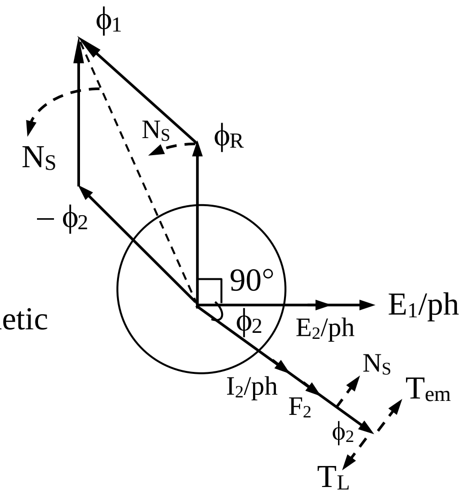
Motoring mode

$$I_2/ph = \frac{E_2/ph}{Z_2/ph}$$

$Z_2/ph = R_2 + jX_2$

$$\phi_2 = \tan^{-1}\left(\frac{X_2}{R_2}\right)$$

Rotor power factor $\text{Cos}\phi_2 = \frac{R_2}{Z_2}$



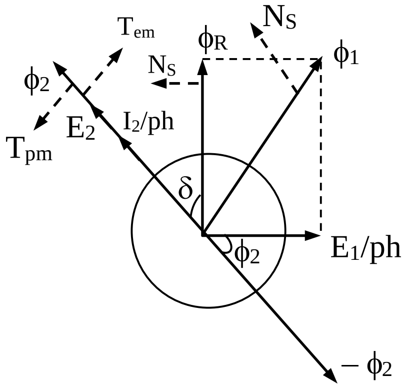
- Relative space angle between the two rotating magnetic fields (ϕ_R & ϕ_2) is $90 + \phi_2$.
  $\bar{\phi}_R = \bar{\phi}_1 + \bar{\phi}_R$
  Stator flux $\bar{\phi}_1 = \bar{\phi}_R + \left(-\bar{\phi}_2\right)$
- Time delay between ϕ_R and ϕ_2 is $\delta = 90+\phi_2$
- T_L = Tem at steady state.
- Nearest field axis to the rotor is resultant field axis ϕ_R

Generating mode

Stator flux $\bar{\phi}_1 = \bar{\phi}_R + (-\bar{\phi}_2)$

At $T_{PM} = T_{em}$, operation of the machine is stable.

Time delay between ϕ_R and ϕ_2 is $\delta = 90 - \phi_2$



☞ In synchronous machine $T \propto \phi_1 \phi_2 \sin\delta$.

☞ The starting torque of the Induction motor will be high when the rotor power factor is high.

If the torque produced by induction motor is in the same direction as that of its rotating magnetic fields, then the machine acts as a motor

If the torque produced by the induction motor is in the direction opposite to its rotating magnetic fields then the machine acts a generator

The relative space displacement between resultant and rotor rotating magnetic field is ($90 + \Phi_2$) in motoring mode of operation ($90 - \Phi_2$) in generating mode of operation which are also called load angle/ torque angle of induction machine.

Torque produced by Induction machine

$T \propto \emptyset_R \emptyset_2 \sin(90 \pm \emptyset_2)$

+ Motoring mode of operation

- Generating mode of operation

Therefore $T \propto \phi_R \phi_2 \cos\phi_2$

Changes in rotor side parameter from stand still to running conditions consequently change in the rotor frequency

R_2= Resistance of the rotor winding/phase

X_{20}= leakage reactance of the rotor at standstill/phase

Z_{20}= Impedance of the rotor winding at staring/phase $=R_2+jX_{20}$

X_2=Leakage reactance of the rotor under running/phase; $X_2=sX_{20}$

Z_2=Impedance of the rotor winding under running conditions/phase$=R_2+jX_2=R_2+jsX_{20}$

E_{20}=EMF induced in the rotor winding during starting/phase

E_2=EMF induced in the rotor winding under running/phase; $E_2=sE_{20}$

I_{20}=Rotor current during staring/phase $= \frac{E_{20}}{Z_{20}} = \frac{E_{20}}{\sqrt{[R_2^2+(X_{20})^2]}}$

I_2= Rotor current under running/phase$= \frac{sE_{20}}{\sqrt{[R_2^2+(sX_{20})^2]}}$

Rotor power factor at starting $\cos \emptyset_{20} = \frac{R_2}{\sqrt{R_2^2+X_{20}^2}}$

Rotor power factor at starting $\cos \emptyset_2 = \frac{R_2}{\sqrt{R_2^2+(sX_{20})^2}}$

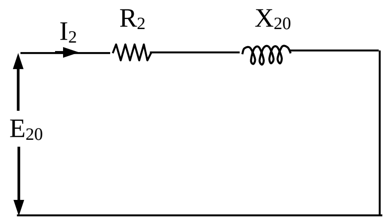
Vector diagram under running condition:

$\delta = 90 + \phi_2$

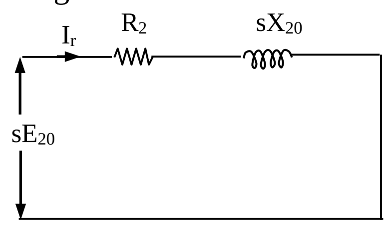
Torque under running condition
$= T \,\alpha\, \phi_R\phi_2 \sin (90 \pm \phi_2)$
$\Rightarrow T \,\alpha\, \phi_R \phi_2 \cos \phi_2$
Torque is proportional to rotor power factor

Equivalent circuits of Rotor:

Rotor equivalent circuit at stand still:



Rotor equivalent circuit under running condition:



As load increases speed will decreases, so slip will increase.

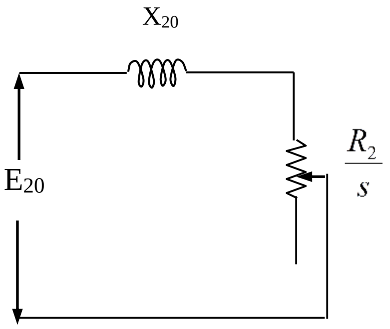
$\therefore$ sX_{20} and sE_{20} will change.

Analysis of rotor with respect to variable (sE_{20}) source is very difficult.

Voltage source SE_2 should be independent on slip s. This can be done as shown below.

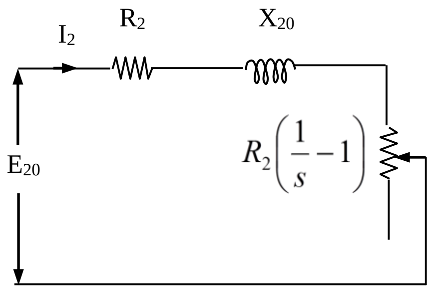
$$I_r = \frac{sE_{20}}{\sqrt{R_2^2 + (sX_{20})^2}} \Rightarrow \frac{E_{20}}{\sqrt{\left(\frac{R_2}{s}\right)^2 + X_{20}^2}}$$

Most preferable representation:



$$\frac{R_2}{S} = \frac{R_2}{S} + R_2 - R_2$$

$$= \underbrace{R_2}_{\text{Winding resistance}} + \underbrace{R_2\left(\frac{1}{S} - 1\right)}_{\text{Variable resistance}}$$



Variable resistance

(Obtained by mechanical load variations)

12. A 1100 V, 50- Hz delta connected induction motor has a star connected slip ring rotor with a phase transformation ratio of 3.8 .The rotor resistance and standstill leakage reactance are 0.012 ohm and 0.25 ohm per phase respectively. Neglecting stator impedance and magnetising current determine.

(i) ***The rotor current at start with slip rings shorted*** ***Ans:1157 A***

(ii) ***The rotor power factor at start with slip ring shorted*** ***Ans:0.048 lag***

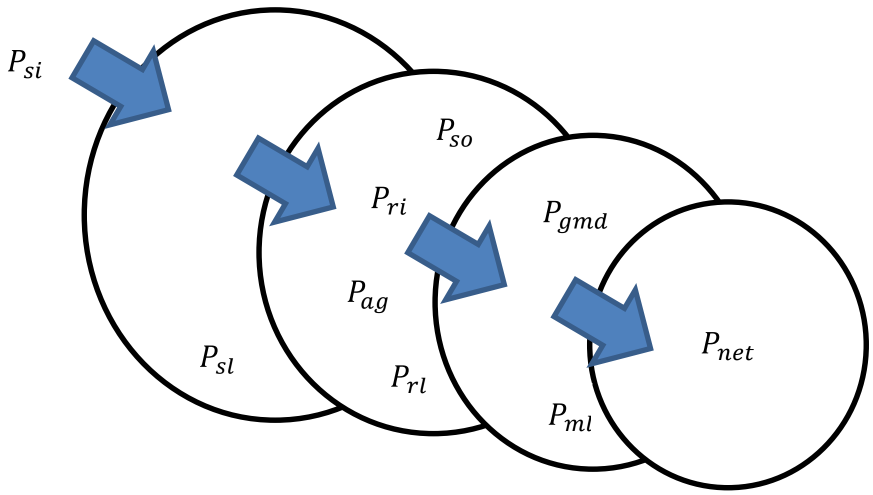
(iii) ***The rotor current at 4 % slip with slip rings shorted*** ***Ans:742.3 A***

(iv) ***The rotor power factor at 4 % slip with slip rings shorted*** ***Ans:0.77 lag***

(v) ***The external rotor resistance per phase required to obtain a starting current of 100 A in the stator supply line*** ***Ans: 0.707 ohms***

(v)$I_2=I_1/K$ =100 x 3.8 =380 A, E_{20}=289.5 A; Z_2=289.5/380=0.7618;
R_2= 0.7616; R_{ext}=0.707 ohms

❖ **Power Flow**



❖ Relationship between rotor input, rotor losses and rotor output power

$$Rotor\ Input\ power(P_{ri}) = 3I_2^2\frac{R_2}{s}$$

$$Rotor\ losses(P_{rl}) = 3I_2^2R_2$$

$$Gross\ mechnical\ power\ developed\ (P_{gmd}) = 3I_2^2R_2\left(\frac{1}{s}-1\right)$$

Rotor copper losses =s× *Rotor input*

Gross mechanical power output = (1-s) *Rotor input*

Rotor copper losses= gross mechanical power output× $\frac{s}{(1-S)}$

Approximate efficiency of rotor:

$$\eta_{rotor} \cong \frac{gross\ mechanical\ power\ output}{rotor\ input}$$
$$= \frac{(1-s)rotor\ input}{rotor\ input}$$
$$= (1-s)$$
$$= 1 - \frac{N_s - N_r}{N_s}$$
$$= \frac{N_s - N_s + N_r}{N_s}$$
$$= \frac{N_r}{N_s} = \frac{speed\ of\ rotor}{synchronous\ speed\ of\ machine}$$

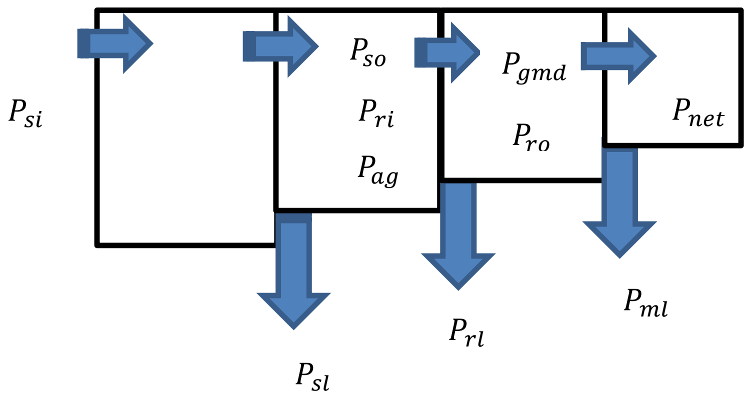
If we want to get more rotor efficiency the operation of the motor the speed of the rotor is nearer to synchronous speed.

Full load slip range = 2 to 8%

Note: As rotor efficiency decrease with increase in slip induction motors are generally designed to operate at low slips ranging from 2 to 8% to have minimum rotor copper losses. There by efficiency of the rotor is increase (high).

Efficiency Calculation:

Model 1 (If the input is given, how to calculate the output and efficiency)



Stator Input (Psi)

(i) If given directly – Psi=40kW

(ii) If is given indirectly , like input current and power factor information is given , in such case, calculate the stator input power using the following equation

$$P_{si} = \sqrt{3}V_L I_L \cos \emptyset_1$$

$where\ V_L\ is\ the\ line\ voltage, I_L\ is\ the\ input\ current\ and\ \cos\emptyset_1\ is\ the\ input\ power\ factor.$

e.g If V_L=400 V, I_L= 50 A, $Cos\Phi_1$=0.866, then P_{si}=30 kW.

A 400 V, 3-phase, 50 Hz, 4 pole star connected induction motor takes a line current of 10 A with 0.86 pf, lagging. What is the stator input?

$$P_{si} = \sqrt{3}V_L I_L \cos \emptyset_1 = \sqrt{3} \times 400 \times 10 \times 0.86 = 5.958\ kW$$

Stator losses:

Stator losses consists of stator copper loss and core losses, and stator core losses consists of eddy current loss and hysteresis loss.

(i) If the total stator losses are given
P_{sl}= 2kW, if P_{si}=40 kW, then stator output $P_{so}/P_{ag}/P_{ri}$=40-2=38kW

(ii) If the stator losses are given separately, like stator copper loss and stator core losses. In such case the total stator losses are sum of stator copper loss and core losses
e.g. Stator copper loss= 1.2 kW and Stator core losses=1kW, then the total stator losses are 1.2 +1 =2.2 kW
e.g., if P_{si}=40kW, then P_{so}=40-2.2 =37.8kW.

(iii) If the information about stator copper loss and total iron losses is given. In such case, the total stator losses are sum of the stator copper loss and total iron losses.
e.g Stator copper loss= 1.2 kW and core losses=1kW, then the total stator losses are 1.2 +1 =2.2 kW
e.g., if P_{si}=40kW, then P_{so}=40-2.2 =37.8kW.
Note: In general, total core losses on induction motor consists of stator core losses and rotor core losses. As stator core losses depends on the supply frequency and the flux density in the iron core. It is practically constant. The iron loss of the rotor is however negligible because frequency of rotor current under normal running condition is always small.
Therefore total core loss means approximately the stator core loss only.

(iv) If the stator losses are expressed as percentage of input power
e.g the stator losses are x% of stator input, then stator losses=$\frac{x}{100} \times P_{si}$
e.g Psi=40kW, if stator losses are 4 % of input power then P_{sl}= $\frac{4}{100} \times 40000 = 1.6\ kW$, then Pso=40-1.6 kW=38.6 kW

(v) If the information about stator core loss, stator winding resistance and input current are given. In such case first calculate the stator copper loss using the following formulae, $3I_1^2R_1$, then sum up with stator core loss, to get total stator losses

$$\boxed{P_{so} = P_{ri} = P_{ag} = P_{si} - P_{sl}}$$

Rotor Losses:

(a) If Information about rotor losses is given directly /indirectly.

(i) If the total rotor losses are given

P_{sl}= 2kW, if P_{si}=40 kW, then stator output $P_{so}/P_{ag}/P_{ri}$=40-2=38kW

If P_{rl}=1 kW, then P_{gmd}=38-1kW=37kW

(ii) If the rotor losses are only given separately and no information about rotor core losses. In such case the total rotor losses are approximately rotor copper loss only

e.g. Rotor copper loss= 1 kW

e.g., if P_{si}=40kW, P_{so}=40-2.2 =37.8kW, then P_{gmd}=36.8 kW

Note: In general, total rotor losses of induction motor consists of rotor copper losses and rotor core losses. The rotor core loss of the rotor is however negligible because frequency of rotor current under normal running condition is always small. **Therefore total rotor loss means approximately the rotor copper loss only**

(iii) If the rotor losses are expressed as percentage of either input power or air gap power

e.g the rotor losses are x% of stator input, then rotor losses=$\frac{x}{100} \times P_{si}$

e.g Psi=40kW, if rotor losses are 2 % of input power then P_{rl}= $\frac{2}{100} \times 40000 = 0.8\ kW$, then P_{so}=40-1.6 kW=38.6 kW; then P_{gmd}=38.6-0.8=37.8kW

(b) ***If Information about rotor losses is not given in such cases the following formulae is used to calculate the gross mechanical power developed.***

$$\boxed{P_{gmd} = P_{ro} = P_{ag} - P_{rl} = P_{ag} - sP_{ag} = P_{ag}(1 - s)}$$

- ***To calculate the gross mechanical power developed, we required air-gap power and also slip***

To calculate slip

(i) If the information about slip is given direction

The power input to a 3-phase induction motor is 60 kW. The stator losses total 1 kW. Find the mechanical power developed if the motor is running with a slip of 3 %

P_{ag}=P_{si}-P_{sl}=60-1=59 kW; P_{gmd}=P_{ag}(1-s)=59(1-0.03)=57.23kW

(ii) If the information about the rotor speed is given , in such case calculate the slip using the formula , $s = \frac{N_s - N_r}{N_s}$

(iii) If the information about the rotor frequency is given, in such case calculate the slip using the formulae, $s = \frac{Frequency\ of\ the\ rotor\ induced\ emf}{Supply\ frequency} = \frac{f_2}{f}$

(iv) If the Information about the number of oscillation of galvanometer, ammeter and voltmeter. In such case, first calculate the rotor frequency using the formulae

$$f_2 = \frac{No.\ of\ oscillation\ of\ galvanometer/voltmeter/ammeter}{60}$$

$$s = \frac{Frequency\ of\ the\ rotor\ induced\ emf}{Supply\ frequency} = \frac{f_2}{f}$$

The power input to a 3-phase, 50 Hz induction motor is 60kW. The total stator loss is 1000W. Find the total mechanical power developed if it is observed that the rotor emf makes 120 complete cycles per minute.

$$f_2 = \frac{No.\ of\ oscillation\ of\ galvanometer/voltmeter/ammeter}{60}$$

$$f_2 = \frac{120}{60} = 2\ Hz$$

$$s = \frac{Frequency\ of\ the\ rotor\ induced\ emf}{Supply\ frequency} = \frac{2}{50} = 0.04$$

$P_{ag}=P_{si}-P_{sl}=60-1=59$ kW; $P_{gmd}=P_{ag}(1-s)=59(1-0.04)=56.64$kW

(v) If the information about X_2 and X_{20} or E_2 or E_{20} are given,

$$s = \frac{X_2}{X_{20}} = \frac{E_2}{E_{20}}$$

Mechanical losses: Mechanical losses consists of frictional losses and windage losses

(i) If the total mechanical losses are given

(ii) If the mechanical losses are expressed as % of either input power/ air-gap power/ of gross mechanical power developed

(iii) If the mechanical losses expressed as torque lost in windage loss and frictional losses

$$\boxed{P_{net} = P_{gmd} - P_{ml}}$$

$$\eta = \frac{P_{net}}{P_{si}} \times 100$$

$$T_{sh} = \frac{P_{net}}{\omega_r}$$

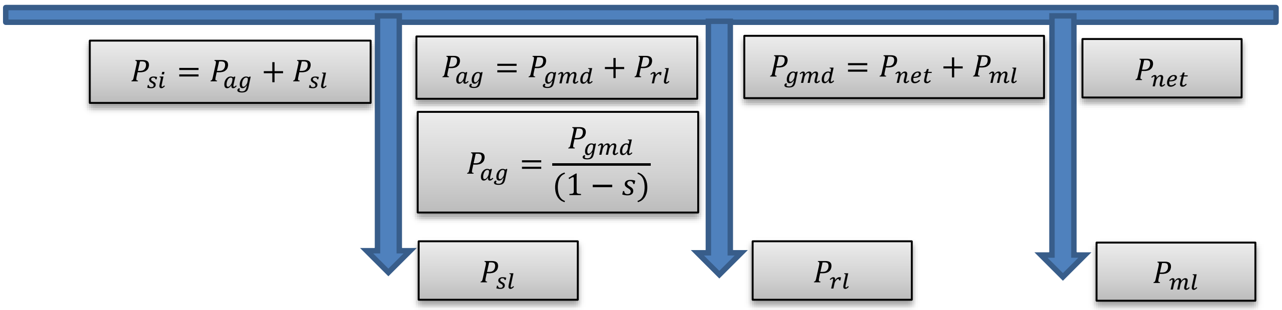
The power input to a 500V, 50 Hz, 6 pole, 3-phase induction motor running at 975 rpm is 40 kW. The stator losses are 1 kW and the friction and windage losses total 2 kW. Calculate shaft power and efficiency

$$N_s = \frac{120f}{p} = 1000\ rpm$$

Nr=975 rpm; P_{sl}=1kW, P_{ml}=2kW; Psi=40kW; $s = \frac{1000-975}{1000} = 0.025$; P_{ag}=P_{si}-P_{sl}=40-1=39kW

P_{gmd}=P_{ag}(1-0.025)=38.025kW; P_{net}=P_{gmd}-P_{ml}=38.025-2=36.025kW;$\eta = \frac{P_{net}}{P_{si}} = \frac{36.025}{40} = 90\%$

Model 2: ***If output is given***



13. The rotor of a 3-phase, 50-Hz, and 4-pole induction motor takes 120 kW at 3 Hz. Determine
(a) Rotor speed and
(b) (b) The rotor copper losses

14. The motor of the problem 14. Has a stator copper loss of 3 kW, a mechanical loss of 2kW, and a stator core loss of 1.7 kW. Calculate
(a) the motor output at the shaft ***Ans: 124.7 kW***
(b) The efficiency, Neglect rotor core losses. ***Ans 89.8%***

15. ***A 6-pole, 3-phase, 60 Hz induction motor take 48kW in power at 1140 rpm. The stator copper loss is 1.4 kW, stator loss is 1.6 kW, and rotor mechanical losses are 1 kW. Find the motor efficiency*** ***Ans:87%***

Approximate torque equation (Stator impedance is neglected)

Mechanical power developed by any rotating machine

$$p = \frac{2\pi N_r}{60} T$$

$$T = \frac{60}{2\pi N_r} p_{gross\ mech\ output} (for\ induction\ machines)$$

$$T = \frac{60}{2\pi N_r} (1 - s)\ rotorinput$$

$$T = \frac{60}{2\pi N_r} \times \frac{N_r}{N_s} \times rotor\ input\ \ \left(1 - s = \frac{N_r}{N_s}\right)$$

$$T = \frac{60}{2\pi N_s}\ rotor\ input$$

$$T \propto rotor\ input\ \ (At\ speed\ of\ N_s\ of\ machine\ )$$

The torque produced by induction motor in this torque produced is directly proportional rotor input at synchronous speed of the machine.

So the unit of torque in induction motor is synchronous watt.

Note:

In induction motor the torque produced by the machine is directly proportional to rotor input power or air gap power at synchronous speed of the machine. The rotor input power in induction motor in synchronous motor.

Synchronous watt: *A 3-∅ induction motor said to be developed one synchronous watt of torque. If one watt of power is transformed from stator to rotor through air gap at synchronous speed of the machine.*

$$T = \frac{60}{2\pi N_s} \times 3I_2^2 \frac{R_2}{s}$$

$$= \frac{180}{2\pi N_s} \left[\frac{sE_{20}}{\sqrt{R_2^2 + (sX_{20})^2}} \right]^2 \frac{R_2}{s}$$

$$T = \frac{180}{2\pi N_s} \frac{sE_{20}{}^2}{R_2^2 + (sX_{20})^2} R_2 \qquad (Approximate\ torque\ equation)$$

Observation of Torque Equation:

1. $T \propto E_{20}^2 \propto E_1^2 \propto V_1^2$
   $T \propto (1.05V_1)^2$
   $\propto 1.05^2 V_1^2$
   $T \propto 1.1025V_1^2$
   If applied voltage is increased by 5%
   If applied voltage is decreased by 10%
   $T \propto (0.9v_1)^2$
   $\propto 0.81V_1^2$
2. If 's' is low
   So sX_{20}<<R SX_2 is very small
   (sX_{20})^2 is neglected
   $$T \propto \frac{SE_{20}^2}{R_2} \propto \frac{SV_1^2}{R_2}$$
   $T \propto s$ Characteristic is straight line
   slip of induction motor i.e. mechanical load increases so torque increases.
3. If 's' is high
   sX_{20}>>R_2 $(SX_{20})^2$>>R_2^2
   So R_2^2 is neglected
   $$T = \frac{180}{2\pi N_s} . \frac{sE_{20}^2 R_2}{(SX_2)^2}$$
   $$T \propto \frac{E_{20}^2 R_2}{SX_2^2}$$
   $$T \propto \frac{V_1^2 R_2}{SX_2^2}$$
   $$T \propto \frac{1}{s}$$
   Torque slip characteristics is a ***rectangular hyperbola.***
4. $T \propto$s operation of induction machine is stable
   $T \propto$ 1/s operation of induction machine is unstable
5. Electromagnetic torque is produced by interaction of two magnetic fields.
   $$T_L - torque\ demanded\ by\ the\ load$$
   $$T_{em} - electromagnetic\ torque\ developed\ by\ the\ machine$$

The induction machine is stable T_{em}=T_L stable operation

6. $T_{max} \rightarrow maaximum\ \ (T_L > T_{max}\ operation\ of\ machine\ unstable)$
7. T_{em}=T_L = stable operation
   $T_L > T_{max}$ = unstable operation

Case 1: Calculating full load torque using approximate torque equation

$$T = \frac{180}{2\pi N_s}\frac{sE_{20}{}^2}{R_2^2 + (sX_{20})^2}R_2 \qquad (Approximate\ torque\ equation)$$

If T =Tfl and s =sfl

$$\textbf{\textit{Then}}\ T_{fl} = \frac{180}{2\pi N_s}\frac{s_{fl}E_{20}{}^2}{R_2^2+(s_{fl}X_{20})^2}R_2$$

16. ***A 3-phase induction motor having a 6 pole, star-connected stator winding runs on 240 V, 50 Hz supply. The rotor resistance and standstill reactance are 0.12 ohm and 0.85 ohm per phase. The ratio of stator to rotor runs is 1.8. Full load slip is 4 %. Calculate the developed torque at full load. Ans: 52.4 Nm***

Case 2: Condition for maximum torque, slip at maximum torque and maximum torque.

Maximum torque = full load torque

Definition: the torque produced by the induction motor which pulls the rotor stable to unstable operating region.

Note: this is the highest torque that can be produced by induction motor for a given design

or

Note: Full load torque is the torque produced by the induction motor which pulls the rotor from stable operating region to unstable operating region.

Pull-out torque: Torque which pulls the synchronous motor out of synchronism

Condition for maximum torque:

We have approximate torque equation given by

$$T = \frac{180}{2\pi N_s}\frac{sE_{20}^2 R_2}{R_2^2 + (sX_{20})^2}$$

The condition and equation for maximum torque can be found using.

Using single variable non-linear optimization problem

Using maximum power transfer theorem.

Using single variable non-linear optimization problem, the condition for maximum torque can be obtained by differentiating the above equation with respect to s and equation it to zero

$$\frac{dT}{dS} = 0$$

Using Maximum power transfer theorem, the direct condition for maximum torque:

Rotor input = $3I_2^2\frac{R_2}{s}$ (maximum power transfer theorem)

T ∝ rotor input

$$\frac{R_2}{s} = X_{20}$$

$$R_2 = sX_{20}$$

$$s_{Tmax} = \frac{R_2}{X_{20}}$$

S_{Tmax} is the slip corresponding to maximum torque and it is known as breakdown slip

Speed of induction motor corresponding to maximum torque

$$N_{Tmax} = N_s(1 - S_{Tmax})$$

$$N_{Tmax} = N_s\left(1 - \frac{R_2}{X_{20}}\right)$$

$$T_{max} = \frac{180}{2\pi N_s} \times \frac{E_{20}^2}{2X_{20}}$$

17. For the above problem maximum torque and slip/speed at maximum torque.

Ans: 99.9Nm, 860 rpm

❖ ***Observations of maximum torque equation***

1. $T_{max} \propto E_{20}^2 \propto E_1^2 \propto V_1^2$

Maximum torque independent of rotor resistance

$$S_{Tmax} \propto R_2$$

2. The maximum torque produced by the induction motor is independent of rotor resistance per phase but the slip corresponding to maximum torque is directly proportional to rotor resistance per phase , that means by inserting external resistance in series with the maximum torque produced by induction motor cannot be increased but by inserting external resistance the maximum torque can be achieved at any desired slip/speed of induction motor
3. $T_{max} \propto \frac{1}{X_{20}}$

   As wound rotor has more leakage reactance when compared to squirrel cage rotor due to presence of windings and windings over hence, the slip ring induction motor has less maximum torque when compared to squirrel cage induction motor

   $$\downarrow T_{max} \propto \frac{1}{X_{20}}\uparrow$$

4. X_{20}(open) < X_{20} (semi open) < X_{20} (fully closed)

   T_{max} (open) > T_{max} (semi open) > T_{max} (closed)
5. If the air gap length between stator and rotor is increased the leakage flux and hence leakage reactance of rotor increases. This in turn decreases maximum torque that can be produced by induction motor.

❖ **Operation of induction motor variable voltage and variable frequency**

$$T_{max} \propto \left(\frac{V_1}{f}\right)^2 \text{; Induction motor}$$
$$E_1/ph = 4.44\ N_{ph}.\ \emptyset_R.\ f.\ K_{w1}$$
$$\emptyset_R \propto \frac{E1/ph}{f} \propto \frac{V_1}{f}$$
$$T_{max} \propto \emptyset_R^2$$

Case 1: Variable V and Variable f with $\frac{V_1}{f}$ ratio is maintained constant

$$\emptyset_R = \text{Constant}$$
$$T_{max} = \text{constant}$$
$$S_{Tmax} = \frac{R_2}{X_{20}}$$
$$S_{Tmax} \propto \frac{1}{f}$$

Frequency reduced by 50% s_{Tmax} becomes by $2s_{Tmax}$

Case 2:- Variable frequency and by keeping voltage constant with $\frac{V_1}{f}$ is not maintained constant

$$\emptyset_r \neq \text{Constant}$$
$$T_{max} \propto (\frac{1}{f})^2$$
$$S_m \propto \frac{1}{f}$$

Case 3: Frequency constant, Voltage is variable

$$\emptyset_r \neq \text{Constant}; \ T_{max} \propto V_1^2$$

Case 3 : Calculating starting torque produced by induction motor

N_r=0, s=1

$$T_{st} = \frac{180}{2\pi N_S} \cdot \frac{E_{20}^2 R_2}{R_2^2 + X_{20}^2}$$

18. For the above problem calculate starting current and starting torque.

Observations of starting torque equation

1. $T_{st} \propto E_{20}^2 \propto E_1^2 \propto V_1^2$
2. R_2 << X_{20} so $(R_2)^2$ << $(X_{20})^2$

   R_2 = 0.1 to 0.2Ω/ph

   X_{20}= 1.5 to 2 Ω/ph

$$T_{st} \cong \frac{180}{2\pi N_S} \cdot \frac{E_{20}^2 R_2}{X_{20}^2}$$

   $T_{st} \propto R_2$ R ↑ T_{st} ↑

   - As there is a provision to insert some external resistance in series with rotor in slip-ring induction motor its starting torque is more than squirrel cage induction motor.

$$T_{st} \propto R_2 + R_e$$

3. $\downarrow T_{st} \propto \frac{1}{X_{20}^2} \uparrow$

   If slip ring induction motor starting without any external resistance its starting torque is slightly less than squirrel cage induction motor because of its less high

leakage reactance of rotor (if external resistance re is inserted in series without wound rotor its starting torque increases)

4. T_{st} (open slot) > T_{st} (semi open slot) > T_{st} (closed)
5. If air gap length between stator and rotor is increased the leakage flux and hence leakage reactance of rotor increases and in turn decreases starting torque produced by induction motor
6. For given whenever the increase in air gap length reduction in starting torque is more when compared to reduction in maximum torque.

❖ **Operation on variable voltage and frequency**

$$T_{st} \propto \left(\frac{V_1}{f}\right)^2 . \frac{1}{f}$$

Case 1: $\boldsymbol{\frac{V_1}{f}}$ ***ratio constant*** $\quad \emptyset_{\boldsymbol{R}}$***= constant***

$$T_{st} \propto \frac{1}{f}$$

Case 2: V_1 constant; frequency is varied

$$T_{st} \propto \left(\frac{V_1}{f}\right)^2 . \frac{1}{f}$$

$$T_{st} \propto \frac{1}{f^3}$$

Case 3: V_1 variable; frequency is constant

$$T_{st} \propto {V_1}^2$$

Case 4: Condition for maximum starting torque and calculating external resistance required in the rotor circuit to obtained maximum starting torque.

$S_{Tmax} = \frac{R_2}{X_{20}}$

At starting S_{Tmax}=1; R_{total}=X_{20}

R_{total}= X_{20}

R_2+R_e = X_{20} (slip ring induction motor); $R_{external}$= X_{20}-R_2

19. For the above problem calculate the additional resistance required to obtained maximum torque at starting

Case 5: Condition for maximum mechanical power output:

Gross mechanical power output $= 3I_2^2 R_2\left(\frac{1}{s}-1\right)$

Maximum power transfer theorem; $R_2\left(\frac{1}{s_{mm}}-1\right)=\sqrt{R_2^2+X_{20}^2}$

$R_2\left(\frac{1}{s}-1\right)$ = internal impedance of rotor at standstill condition

$$s_{mm}=\frac{R_2}{R_2+\sqrt{R_2^2+X_{20}^2}}$$

20. ***For the above problem, calculate the maximum mechanical power and slip at maximum mechanical power.***

Ratio's between different torques

(i) $T_{fl}=\frac{180}{2\pi N_s}\cdot\frac{S_{fl}E_{20}^2R_2}{R_2^2+\left(S_{fl}X_{20}\right)^2}$

(ii) $T_{max}=\frac{180}{2\pi N_s}\cdot\frac{E_{20}^2}{2X_{20}}$

(iii) $T_{st}=\frac{180}{2\pi N_s}\cdot\frac{E_{20}^2R_2}{R_2^2+X_{20}^2}$

(iv) $\frac{T_{fl}}{T_{max}}=\frac{2as_{fl}}{a^2+s_{fl}^2}$

$$a=\frac{R_2}{X_{20}}=S_{Tmax}$$

$$\frac{T_{fl}}{T_{max}}=\frac{2S_{Tmax}S_{fl}}{S_{Tmax}^2+S_{fl}^2}$$

$$\frac{T_{fl}}{T_{max}}=\frac{2}{\left(\frac{S_{Tmax}}{S_{fl}}\right)+\left(\frac{S_{fl}}{S_{Tmax}}\right)}$$

e.g full load slip= 80% of s_{Tmax}; S_{fl}= 80% of

$\frac{T_{fl}}{T_{max}} = \frac{2}{(0.8)+\left(\frac{1}{0.8}\right)}$=0.96

(v) $\frac{T_{st}}{T_{max}} = \frac{2a}{a^2+1}$

(vi) For induction motor, R_2=0.1 to 0.2 ohms and X_{20}=1.5 to 2.0 ohms slip is ranging from 2 to 8 %, As such $(sX_{20})^2 <<<<<<<<< R_2^2$

T =$\frac{180}{2\pi N_S} . \frac{sE_{20}^2 R_2}{R_2^2}$; E_{20} approximately equal to V_1=V (supply Voltage)

T =$\frac{180}{2\pi N_S} . \frac{sV^2}{R_2}$ and $T \propto \frac{sV^2}{f}$

21. A 230V, 6 pole ,3 –phase , 50Hz, 15kW induction motor drives a constant torque load at rated frequency rated voltage and rated kW output and has a speed of 980 rpm and has an of 93% calculate (i) the new operating speed if there is a 10% drop in voltage and 5% drop in frequency and (ii) new output power. Assume all losses to remain constant Ans:928 rpm, 14.2 kW

22. A 3-phase, 400/200 V, Y-Y connected wound – rotor induction motor has 0.06 ohm rotor resistance and 0.3 ohm standstill reactance per phase. Find the additional resistance required in the rotor circuit to make the starting torque equal to the maximum torque of the motor. Ans: 0.24 ohms

23. ***A 3-phase, 50- Hz, 8 pole, induction motor has full load slip of 2%. The rotor resistance and stand still rotor- reactance per phase are 0.001 ohm and 0.005 ohm respectively. Find the ratio of the maximum to full load torque and the speed at which the maximum torque occurs.*** ***Ans:*** $\frac{T_{max}}{T_{fl}} = 252.5; \frac{T_{fl}}{T_{max}} = 3.96\ x\ 10^{-3}$

Load types:

The characteristics of motor have to match the characteristics of the load which the motor is driving. These loads can be divided into four types viz.

(a) Load torque proportional to square of the shaft speed

(b) Load torque proportional to the shaft speed

(c) Load torque independent of the shaft speed (or constant torque) and

(d) Load torque inversely proportional to shaft speed. These four load characteristics are shown in fig.

It is important to remember that power = (torque) (speed)

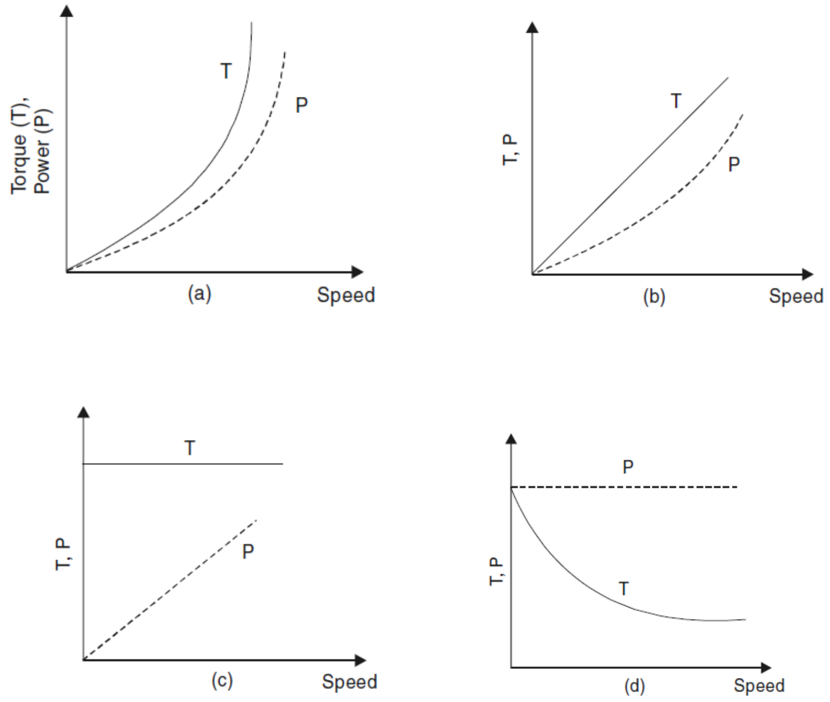


Fig: load characteristics (a) torque ∝ $(speed)^2$, (b) torque ∝ speed, (c) torque= constant, (d) torque ∝ $1/speed$.

Type a	Type b	Type c	Type d
Torque ∝ $(speed)^2$ Power ∝ Torque×speed ∝ $(speed)^3$ It is very suited for energy conservation Example are: Axial and centrifugal pumps, axial and centrifugal ventilators, centrifugal compressors, centrifugal mixers, agitators etc.	Torque ∝ speed Power ∝ Torque×speed ∝ $(speed)^2$ Examples are: Mixers, stirrers, etc.	Torque= constant Power ∝ Torque×speed ∝ $(speed)$ Examples are: Conveyor machines, lift machines, extrusios, draw benches etc.	Torque ∝ $1/speed$ Power ∝ Torque×speed Or Power=constant Examples are: Lathes, wire drawers,reciprocating rolling mills, wind machines etc.

❖ **Torque speed (or) Torque slip characteristics of 3ϕ Induction machine**:

$$T_{em} = \frac{KsE_{20}^2R_2}{R_2^2 + (sX_{20})^2}$$

The total torque characteristics are divided into three regions

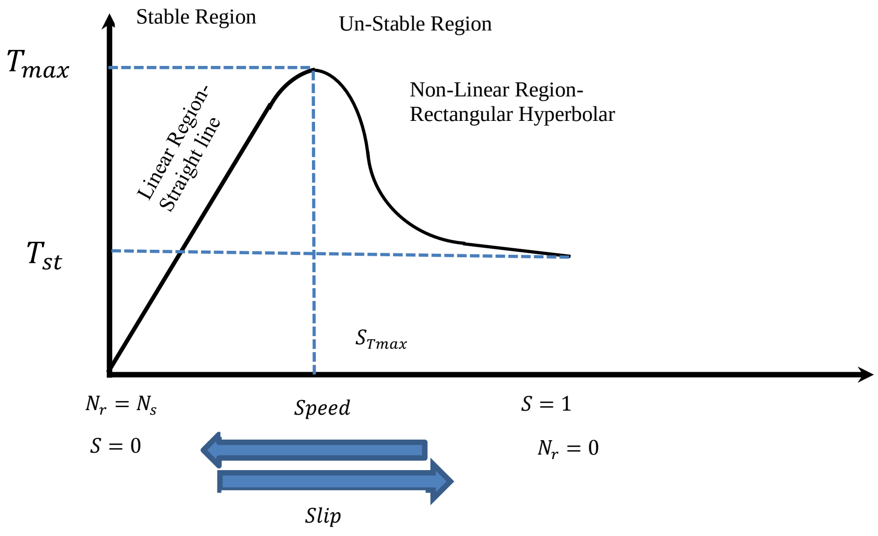
❖ Low slip regions/lightly loaded conditions

$$N_r \cong N_s\,; s \cong 0; (sX_{20})^2 \lll\lll< R_2^2\,; T\alpha s$$

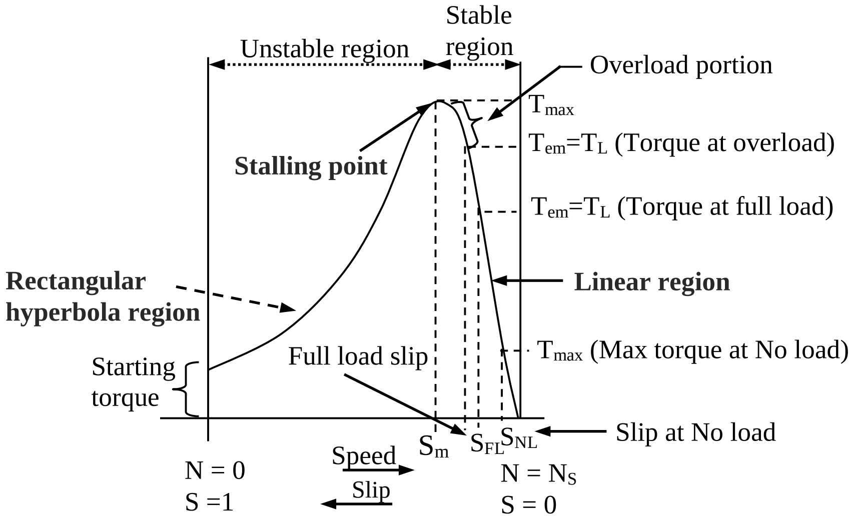
❖ Medium slip region

❖ High slip regions

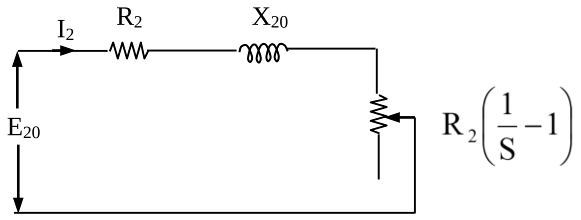
$$N_r < N_s\,; s; (sX_{20})^2 \lll\lll< R_2^2\,; T\alpha 1/s$$



. In motoring mode: ($0 \le N < N_S$ and $0 < s \le 1$)
Even at $N_r = 0$ motor will produce torque is called starting torque.



- At low value of slip $T_{em} \alpha\ s$
- At high value of slip $T_{em} \alpha\ 1/s$
- In stable operation the range of 's' is $0 < s \le s_m$
- In unstable operation the slip range is $s_m < s \le 1$

▪ 

If load increase then s↑

$\Rightarrow R_2\,(1/s - 1) \downarrow$

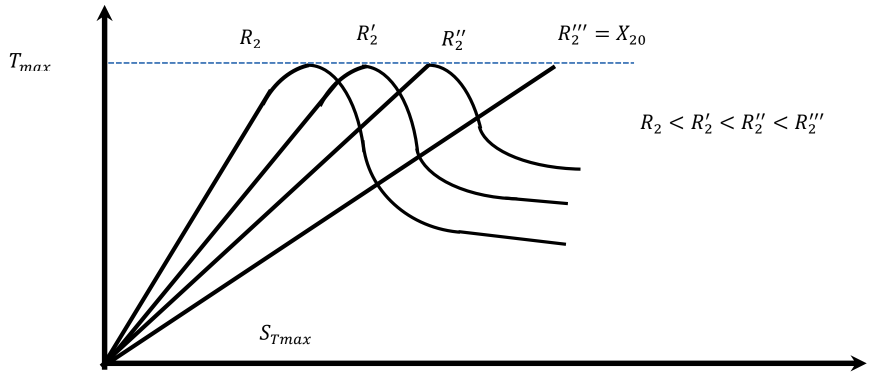
$\Rightarrow I_2 \uparrow$

$\therefore$ Supply current (stator current) of to the motor increases.

$\bar{I}_1 = \bar{I}_0 + \bar{I}_2$

Motor current I_1 increases and finally reaches to full load current and then that load corresponding to full load current is full load on motor and induction motor is said is be fully loaded. The motor will draw the current more than rated current whenever the load is increased beyond the full load and this condition is called condition over load condition. The speed variation form No load to full load is very less, hence Induction motor can be treated as constant speed motor like DC shunt motor.

Family of Torque slip characteristics with different rotor winding resistance:



$$R_2 \uparrow, S_{Tmax} \uparrow, T_{st} \uparrow \; but \; T_{max} = Constant, we \; can \; increase \; once \; R_2 = X_{20}$$

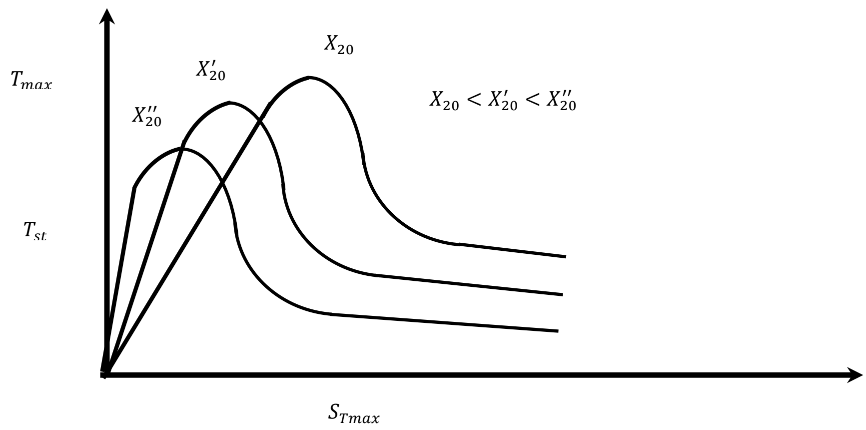
Whenever R_2 is increased, we cannot increase the maximum torque, but we can increase the starting torque.

Increase in R_2 increases the stable operating region(Disadvantage for Induction motor is that, width of the stable operating region is very low, as rotor winding resistance R_2 is very low) to perform good operation.

Note:* *The winding resistance of the rotor increases the stable operating region, and stable operating region become wider and operating point is moving away from the synchronous speed, which results in poor performance of the machine. That's why the winding resistance of the rotor should not be high, but it should be low to get a narrow stable operating region and hence good performance of the machine.

If the starting torque of machine of the machine need to be increased, that can be done by adding an external resistance in the rotor circuit at the time of starting.

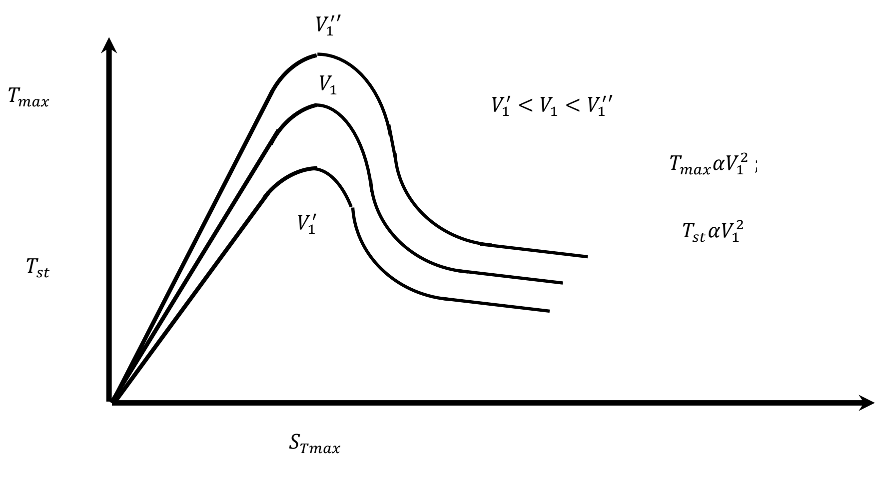
Family of torque slip characteristics with different rotor reactance.



$$\downarrow T_{max} \alpha \frac{1}{X_{20} \uparrow} \; ; \downarrow s_{Tmax} \alpha \frac{1}{X_{20} \uparrow} ; \downarrow T_{st} \alpha \frac{1}{X_{20}^2 \uparrow}$$

If reactance is increased the family of torque slip characteristics shifts to right side and also maximum torque decreases, slip at maximum torque decreases and also starting torque decreases

Family of torque slip characteristics with different stator voltage.



Generator mode: (N_r>N_S and the slip range is $-\infty < s < 0$)

$$S = \frac{N_S - Nr}{N_S} \approx -Ve$$

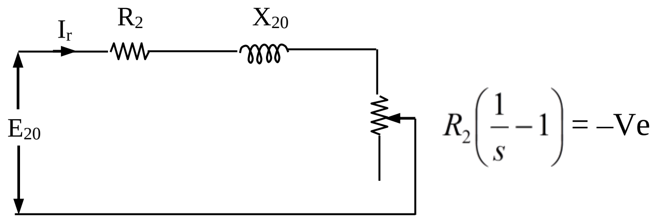


Fig: Rotor under generating mode.

The output resistance is negative means the output power developed is electrical power not a mechanical power.

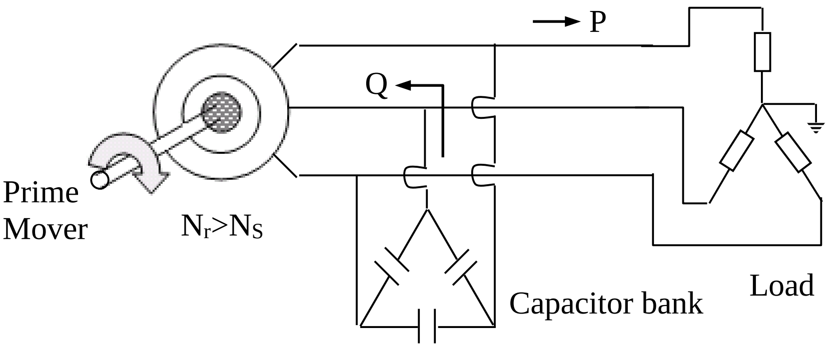


Fig: Reactive power consumption in generating mode

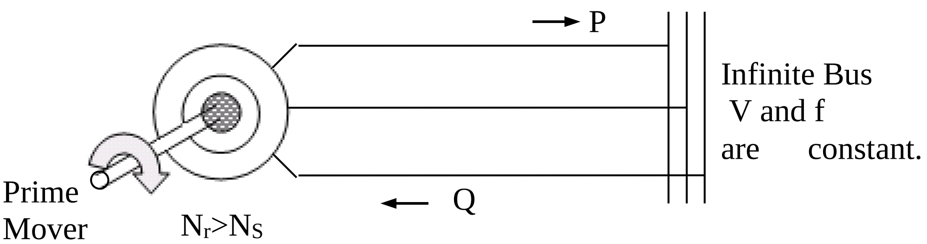


Fig: Reactive power consumption in generating mode

- The induction generator is equivalent to an under exited synchronous generator because it consumes reactive power to create its rotating magnetic field and in turn to produce active power.
- Gross electrical power output = $3I_2^2R_2\left(\frac{1}{s}-1\right)$
- Stator Input power (Air gap power) = Gross electrical power output – Rotor copper loss
- Losses in stator are copper losses and core losses.
- Net electrical power output = stator input power – stator losses.

☞ In generating mode, torque is opposite to that of rotating field so torque – slip characteristic is negative and is as show below.

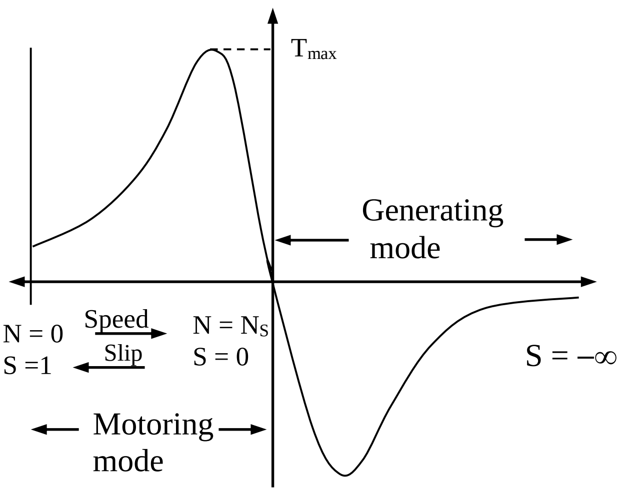


Fig: Induction machine characteristics in motoring and generating mode

Important features of induction generator

1. In isolated induction generator a delta connected capacitor bank across stator is used to supply reactive power to enable the machine to create the rotating magnetic field
2. Whenever the induction generator is connected to grid, no capacitor bank is required and machine draws the reactive power from the grid itself to create the rotating magnetic fields
3. Induction generator is just equal to under excited synchronous generator
4. In order to have negative slip in induction generators with low speed prime movers such as wind turbine, the following techniques can be employed
   (i) Induction generator should be made up with more number of poles, (of order 20 (or) 24)
   (ii) In order to step up the speed of the prime mover a gear box is used in between the prime mover and rotor such as 1:5 or 1:10
5. In order to power at grid frequency by induction generator(AC to DC and AC cascaded inverter are used
6. Torque produce by the induction generator is negative

Electrical Braking Mode in Induction motor:

The three main methods of Electrical braking are

1. Plugging (or counter current braking)
2. Dynamic (or rheostatic) braking:
3. Regenerative braking:

Plugging:

In this case electrical braking is made first to reduce the speed of the motor near to zero and later mechanical brakes has to apply to take the motor speed to zero.

The direction of rotation of magnetic field is reversed by changing a pair of stator leads while a motor is rotating, torque is suddenly produced opposite to the original direction of rotation this torque acts as a Braking torque to the motor and motor is in Breaking mode.

This reverse torque causes rotation in the opposite direction as soon as the motor stops, therefore provision must be made to disconnect stator completely from the supply lines when the motor stops.

Rheostatic braking:

In this method Induction motor can be realized by disconnecting the stator winding from the A.C supply and exiting it from D.C source to produce a stationary D.C field.

The advantages over plugging are:

1. The absence of the reverse-rotation air gap field and therefore no tendency for the machine to run backwards.
2. Lower rotor I^2R losses.

Regenerative braking:

When an induction motor runs at speed above synchronous speed, it operates as an induction generator and feeds power back to the supply lines; thus regenerative braking is an inherent characteristic of an Induction motor.

The above synchronous speed will be obtained by switching over to a large no. of pole operation from a smaller one in multi speed squirrel cage motors.

Based on plugging method:

In braking mode the torque direction and rotating field directions are reversed but not rotor direction.

$\therefore$ slip $= \dfrac{N_S - (-N)}{N_S}$; up to speed of rotor comes to zero.

$\Rightarrow s > 1.$

The range of slip is $1 < s \leq \infty$

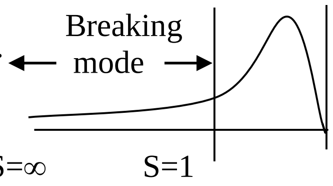
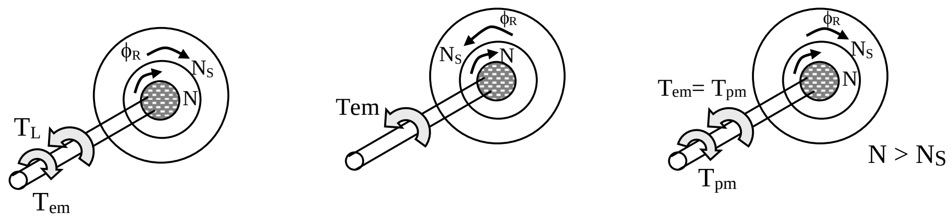


Fig: Torque – Slip characteristic

Shaft conditions:



Motoring Mode Braking Mode Generating Mode

Motoring mode	Breaking mode	Generating mode
1.Torque T_{em} = +Ve 2.Speed N = +Ve 3.Mechanic power output is positive	1.Torque T_{em} = +Ve 2.Speed N = –Ve 3.Mechanic power output is negative(Kinetic energy is gradually consumed)	1.Torque T_{em} = –Ve 2. Speed N = +Ve 3. Mechanic power output is negative

Power– slip speed characteristics of 3ϕ Induction motor:

Mechanical power output $P = \dfrac{2\pi NT}{60}$

At speed N = 0, power P = 0,

At speed N = N_S, torque T = 0 and power P = 0.

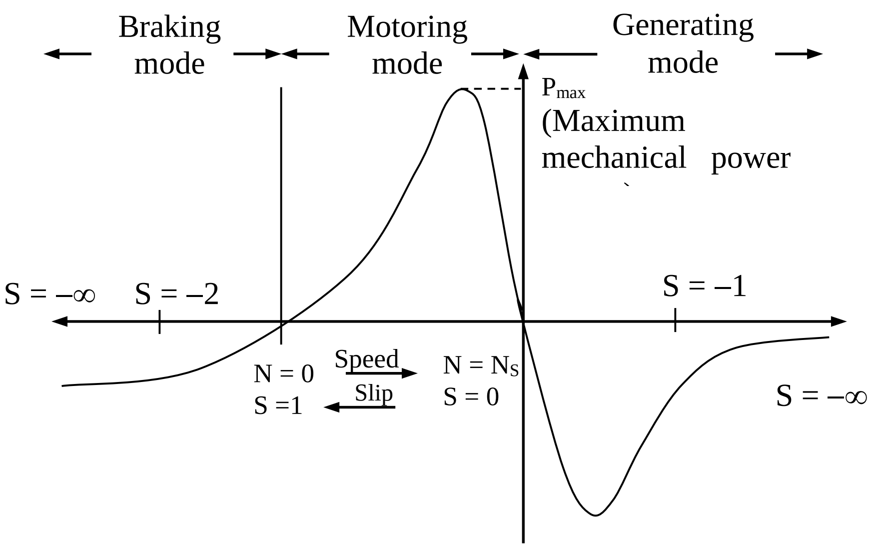


Fig: Power-Slip characteristics of Induction machine